TESLA

Linac Optimization for PAL XFEL Project

January 7th, 2004

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POSCO = the World's Largest Steel Company

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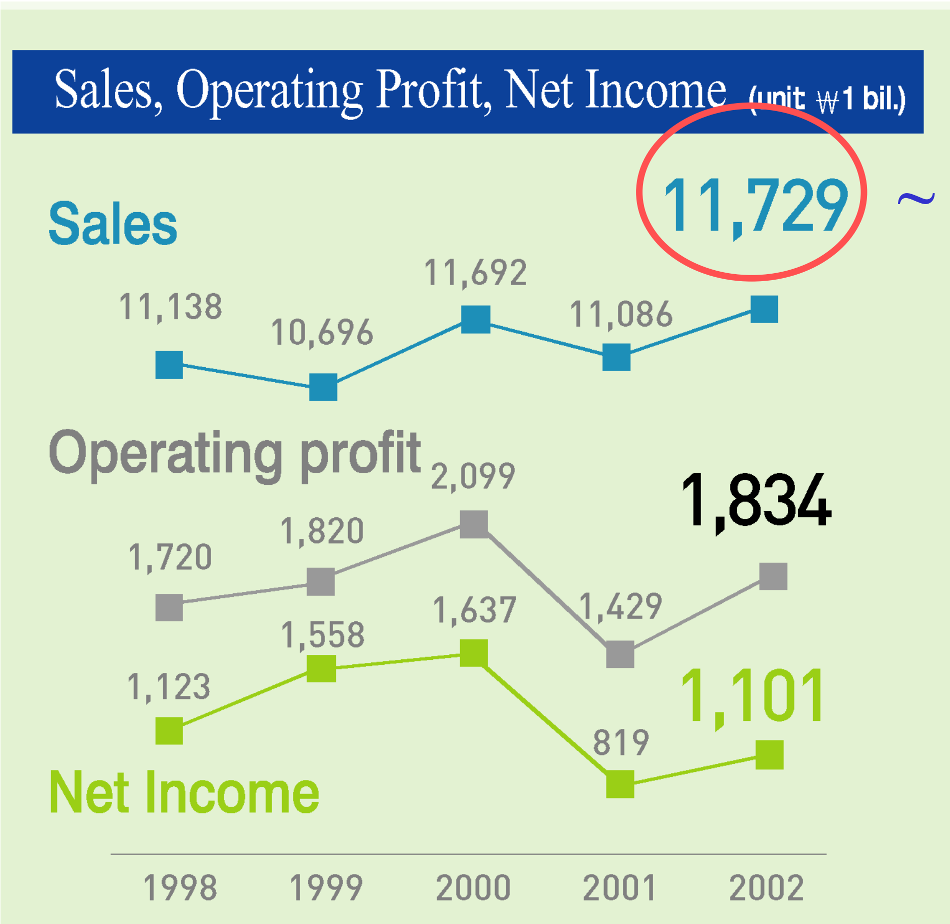
POSCO estabilished the first research intensive university in Korea,

Pohang University of Science and Technology (POSTECH) in 1986,

and

Pohang Accelerator Laboratory (PAL) with a 3rd generation light source (PLS) in 1988.

POSCO = the World's Largest Steel Company



~ 9100 M$

~ 153 M$

POSCO invested about 1.6% of its Sales in R&D in 2002.

(about 17% of its net income)

POSTECH = The Korea's Premier University

POSTECH got many donations from POSCO

For university future, 133 M$ in 2000
For the largest library in Korea, 42 M$ in 2001
For a biological research center, 27 M$ in 2002

In 1998 Asiaweek ranked POSTECH "No.1"
among the specialized sciences and technology universities in Asia.

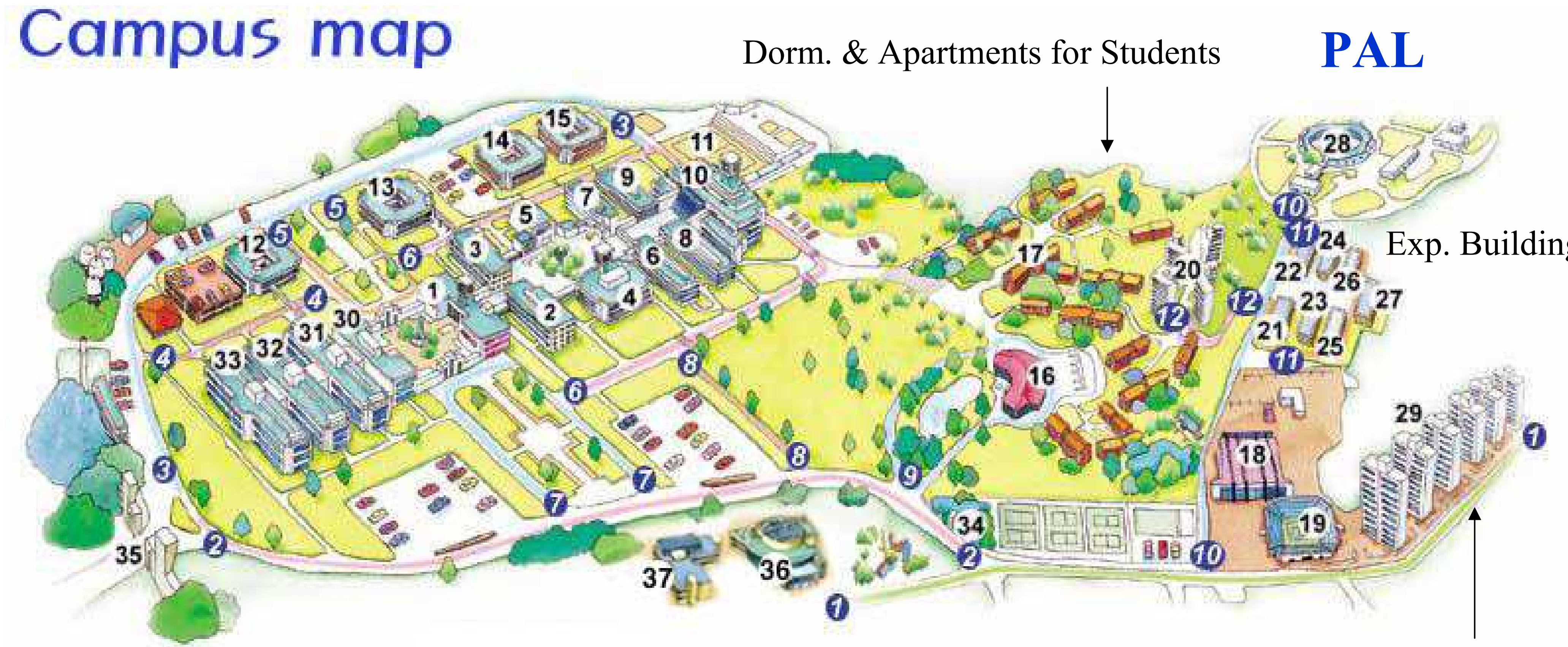
In 1994, 1996, 1997, 2002, and 2003, the Joong-Ang Ilbo, a Korean daily newspaper, ranked POSTECH the "No.1" university in Korea.

Huge Scientific Campus of POSTECH

POSTECH

Dorm. & Apartments for Students

PAL



Exp. Buildings

Biological Research Center

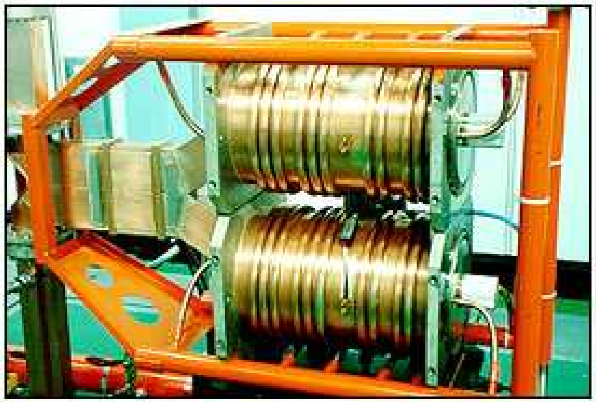
Digital Library

Apartments for Professors

Pohang Accelerator Laboratory (PAL)

Current PLS 2.5 GeV S-band Linac

- Frequency : 2856 MHz
- Total length : 160 m
- Beam Energy : 2.5 GeV
- Energy spread ≤ 0.6%
- Bunch length : 17~20 ps
- Beam current : ~ 1.0 A
- Normalized emittance : 130 μm

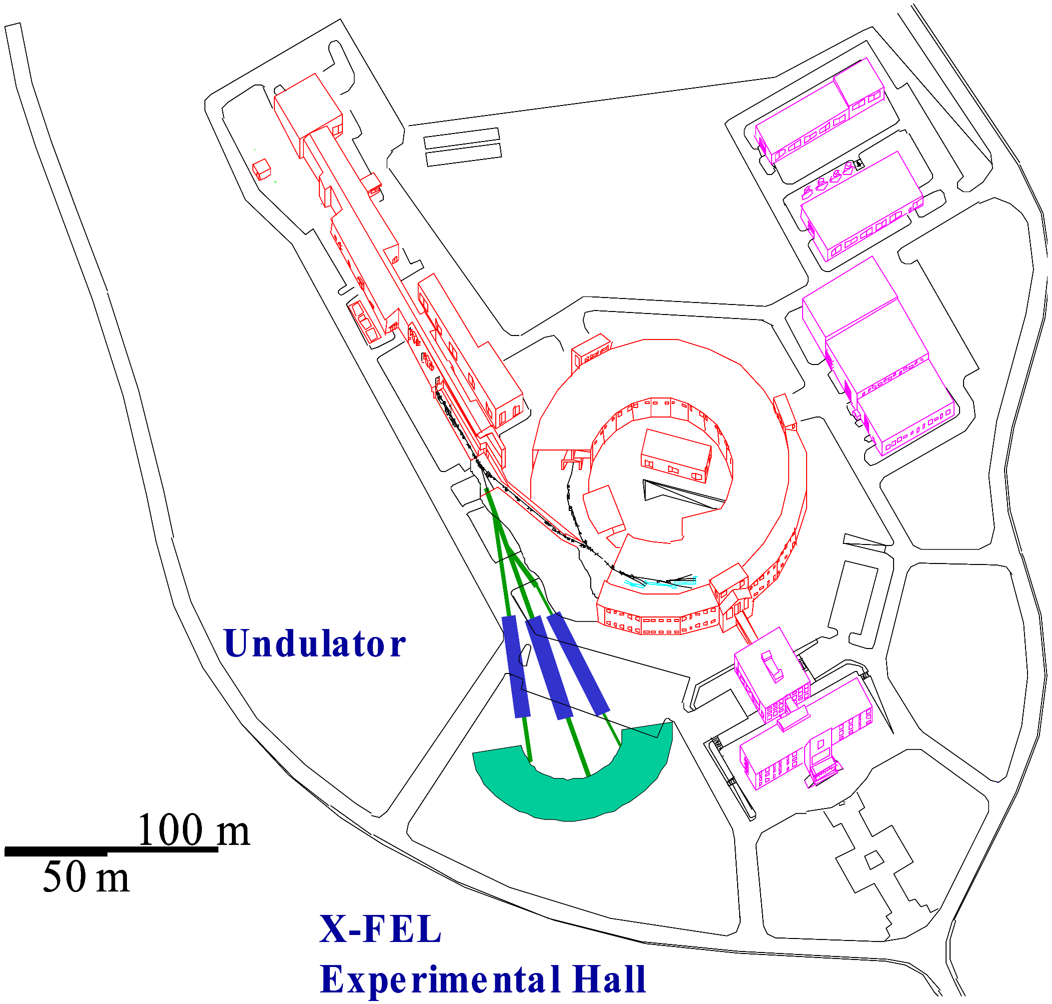


PAL XFEL Project

For 3.0 Å PAL XFEL Project:

Courtesy of J. S. Oh

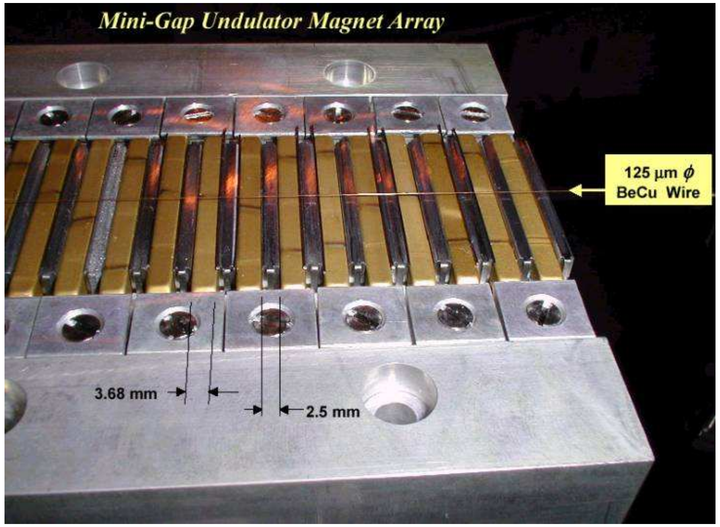
Existing 2.5 GeV S-band PLS Linac
+ New S-band Photoinjector
+ New 0.5 GeV Linac
+ New Two Bunch Compressors
+ New ~ 60 m long Undulator

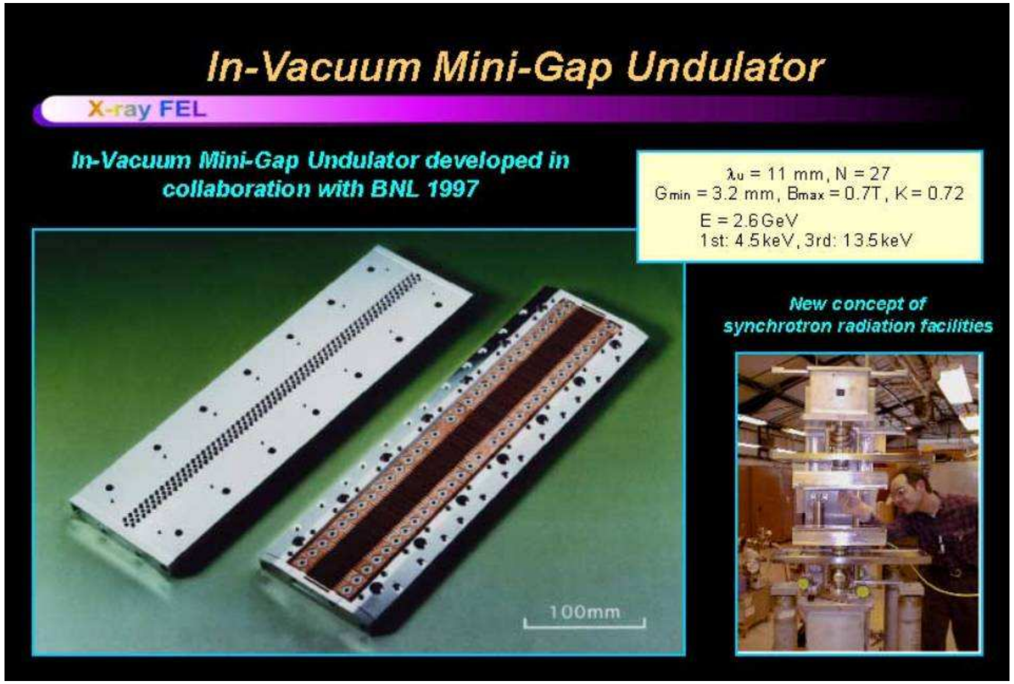


Undulator for PAL XFEL Project

Parameter \ Device	PSGU (1993)	IVUN (1997)	MGU (2002)	MGU (2003)
	X13			X29
Type	Pure PM	Pure PM In-Vacuum	Hybrid PM In-Vacuum	Hybrid PM In-Vacuum
Period λ_u	16 mm	11 mm	12.5 mm	12.5 mm
No. of Periods	18	30.5	27	27
Nom.Mag.Gap	6.0 mm	3.3 mm	3.3 mm	3.3 mm
Peak Field B_u	0.62 T	0.68 T	1.0 T	1.0 T
K_{max}	0.93	0.7	1.17	1.17
Fund. Energy @ 2.8 GeV	3.2 keV	5.4 keV	3.5 keV	3.5 keV

We will use **in-vacuum mini gap undulator**, which was developed by **SPring-8 and BNL**.





Estimated Budget for PAL XFEL Project

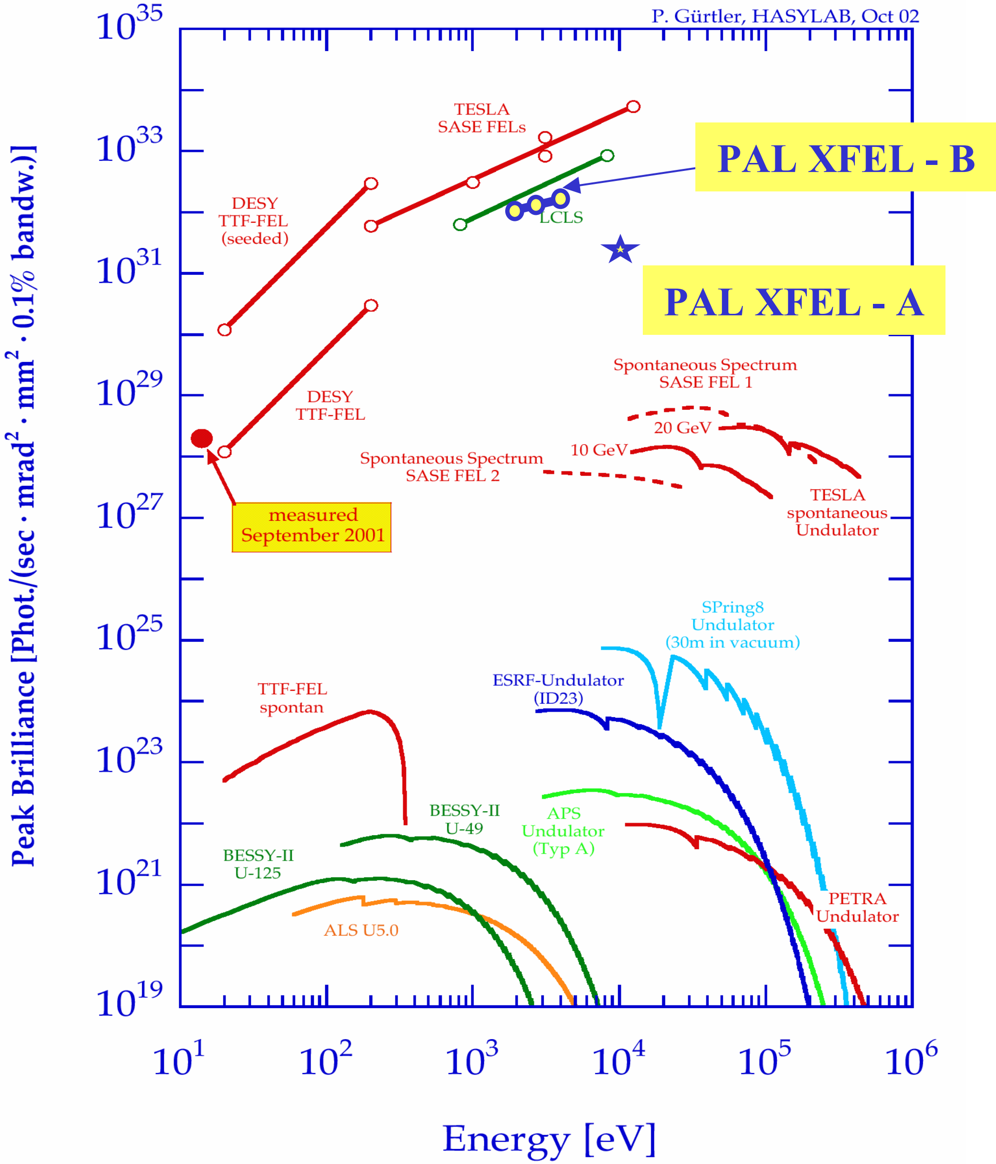
Courtesy of J. S. Oh

Undulator	15 B KRW	(13M$)
Main Linac	13 B KRW	(11M$)
Conventional Facility	11 B KRW	(9M$)
Beam Line	7 B KRW	(6M$)
Contingency	4 B KRW	(3M$)
Total	50 B KRW	(42M$)

Notes;

1) 13 units of of 4.5-m undulator and 1.0 M$ per undulator
2) X-FEL linac = 1 pre-injector + 2 new linac modules
3) 1.5 M$ per 12-m linac module, 3.0 M$ for pre-injector, 2.0 M$ for bunch compressors and subsystems, 3.0M$ for main linac upgrade

PAL XFEL Project



Courtesy of J. S. Oh

	A	B
λ_x (Å)	1.0	3.0
ε_n (μm)	1.0	1.5
τ (fs)	20	233
λ_u (mm)	6.5	12.5
gap (mm)	3.0	3.0
K	0.4	1.14
β(m)	30	15
L_u(m)	22.5 + 36	58.5
PB ($x10^{32}$)	0.4	1.4

A: HGHG layout with B undulator

Accelerator Parameters for PAL XFEL Project

For the Microbunching in Undulator

- **Slice normalized rms emittance:**

$$\varepsilon_{ns} < \gamma \frac{\lambda}{4\pi}$$

- **Slice rms relative energy spread:**

$$\sigma_{\delta s} < \rho \approx \frac{1}{4}\left[\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_n}\left(\frac{K}{\gamma}\right)^2\right]^{1/3}$$

- **Total undulator length:**

$$L_u > L_{sat} \approx L_G \ln\left(\frac{P_{sat}}{\rho E e \Delta\omega}\right) \approx 20 L_G$$

where $L_G \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$

$$\lambda_{\min} \propto \frac{\varepsilon_n^{5/4}}{L_u^{3/2} I_{pk}^{3/4}}\left[1 + 6\left(\frac{\sigma_{\delta s}}{\rho}\right)^2\right]^{1/2}$$

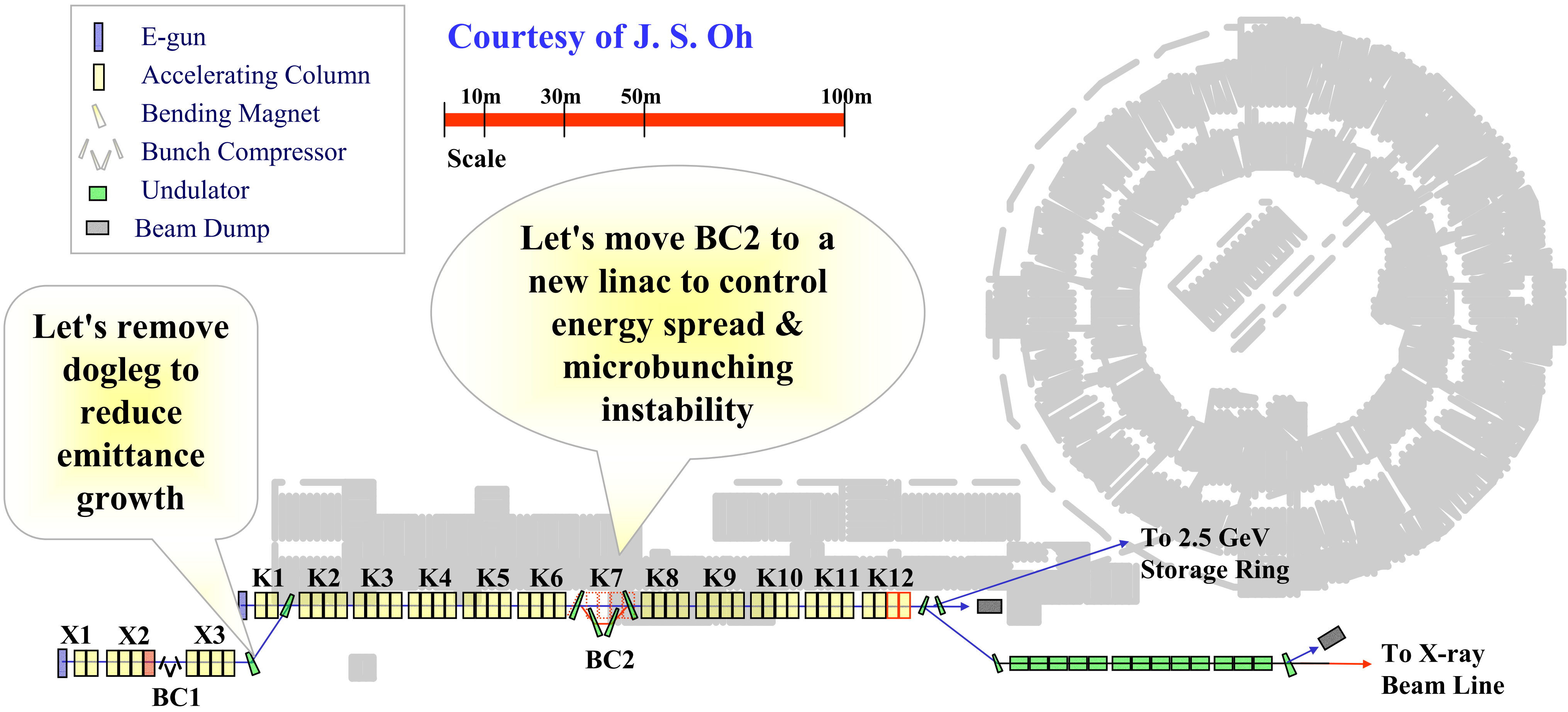
Low emittance & high peak current !!!

For 3 Å PAL-XFEL Project

Electron beam energy	≥	**3.0 GeV**
rms bunch length	≤	**100 fs = 30 μm**
Normalized slice emittance	≤	**1.5 μm**
Slice rms energy spread	≤	**0.02% = 600 keV**
Peak current	≥	**4.0 kA**

Courtesy of J. S. Oh

Original Linac Layout for PAL XFEL Project

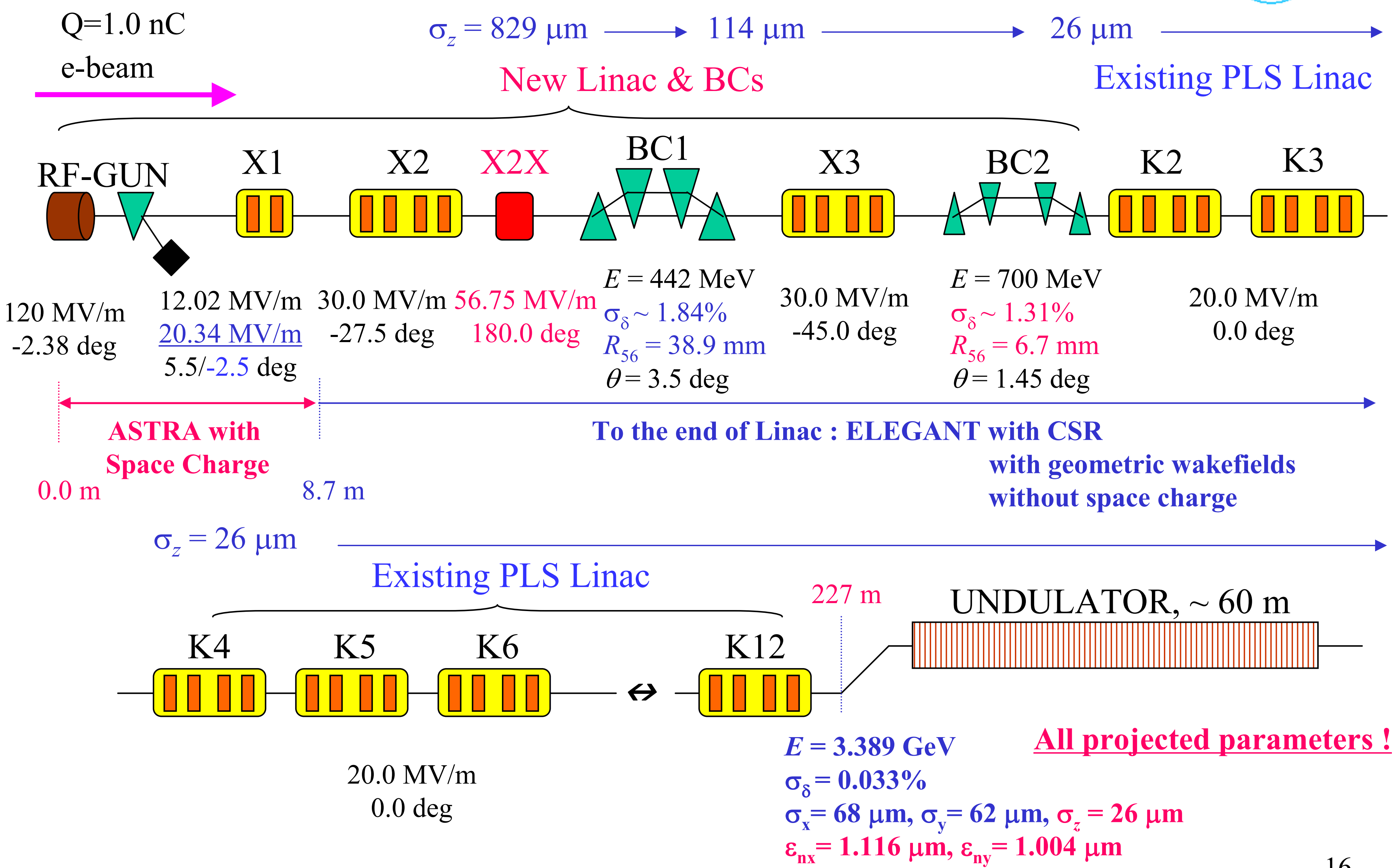


New 0.5 GeV Linac
X1=150 MeV
X2=100 MeV
X3=250 MeV

Existing 2.5 GeV PLS Linac
K1= 100 MeV Injector
K2~K6, K8~K12=250 MeV
BC2 @ K7 + 2 A/C @ K12

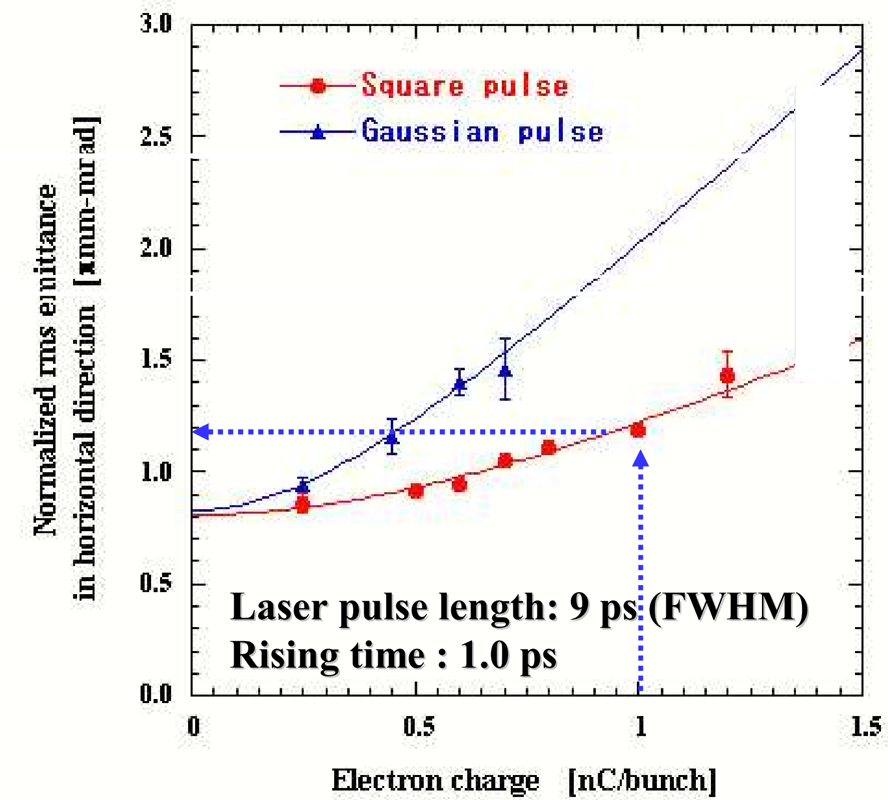
New Undulator (λ_x=0.3 nm)
E_o=3.0 GeV, ε_n=1.5um-rad
I_P=4.0 kA, σ_E=0.02%
λ_U=1.25 cm, g=3.0mm, L_U=58.5 m

New Layout for PAL XFEL - 05DEC03 Version



S-band LCLS/BNL Type Photoinjector

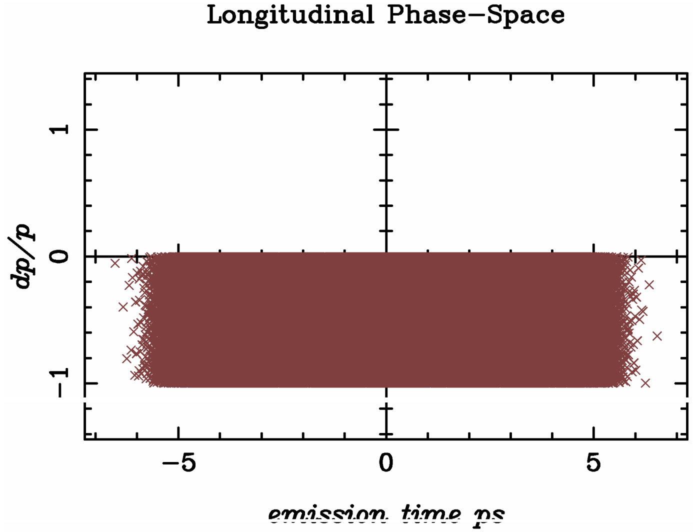
Measured Emittances by Sumitomo SHI + FESTA
(Journal of Applied Physics, Vol 92, No 3, p. 1608 by J. Yang et al.)

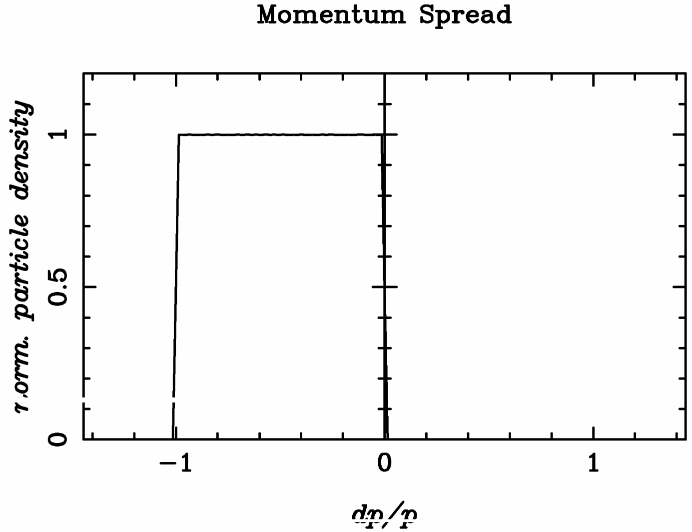


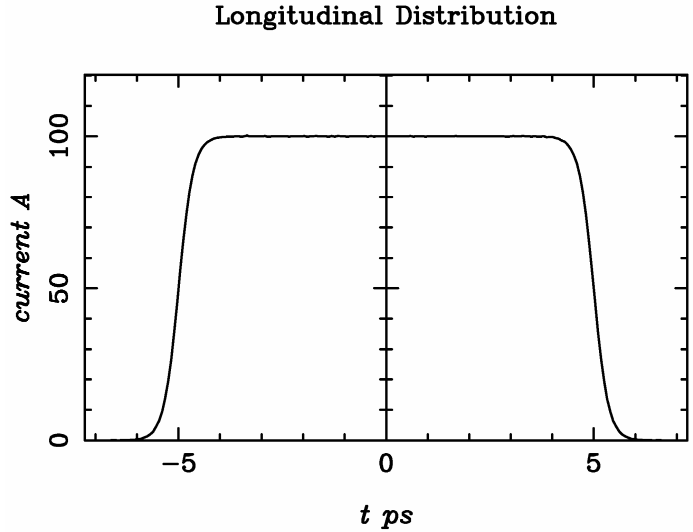
Let's use LCLS type S-band photoinjector as an injector for PAL XFEL project !!!

ASTRA Simulation for LCLS Injector

At cathode



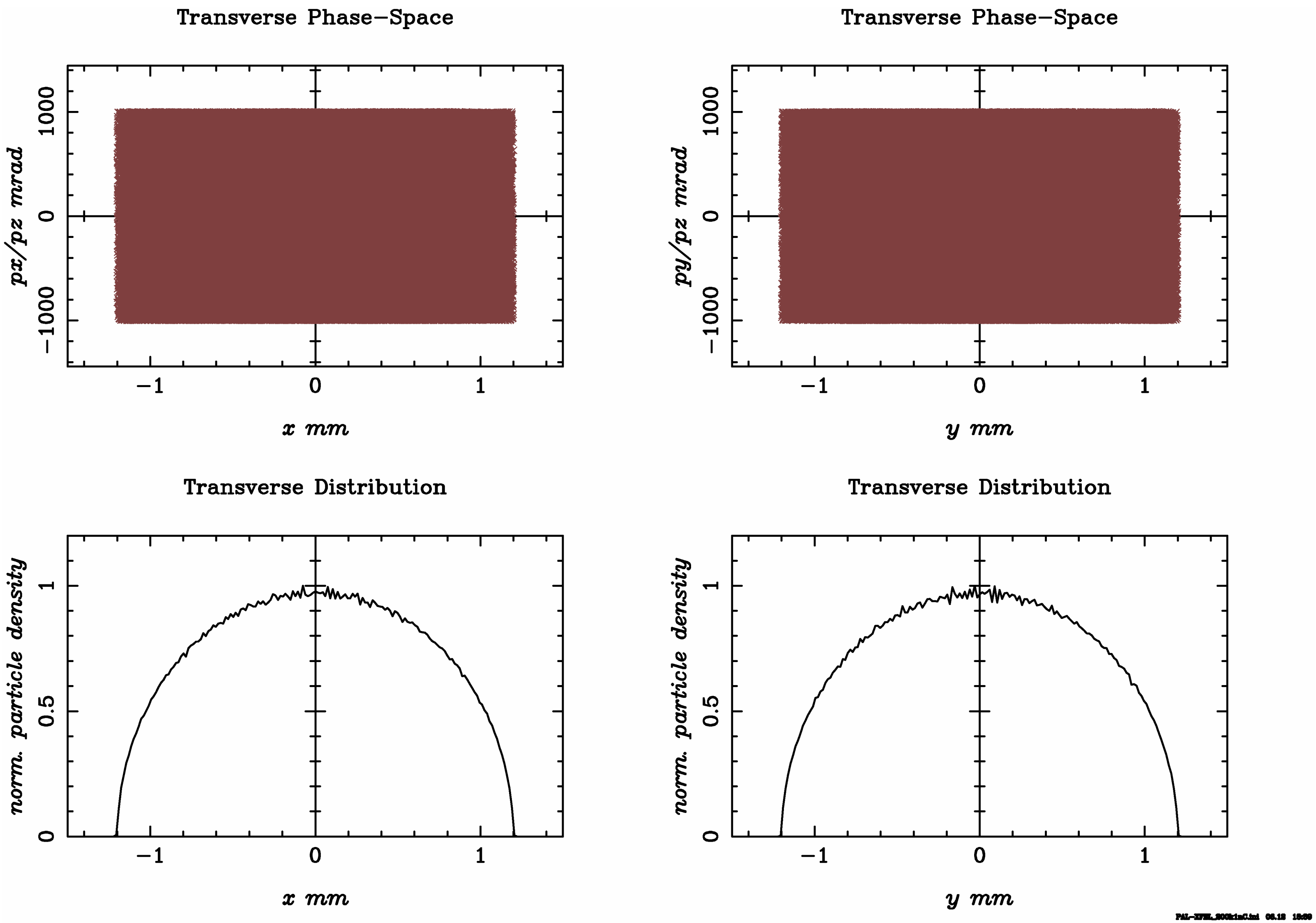




Bunch length at cathode : 10 ps (FWHM)
2.9 ps (rms)
Rising time : 0.7 ps
Spot size : 0.6 mm
Thermal emittance : 0.6 μm
Peak gradient at cathode : 120 MV/m
Peak solenoid field : 2.71 kG at 19.1 cm

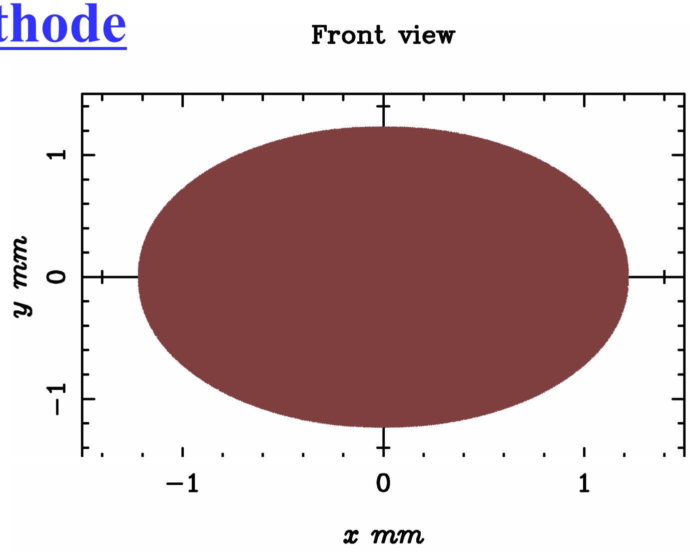
ASTRA Simulation for LCLS Injector

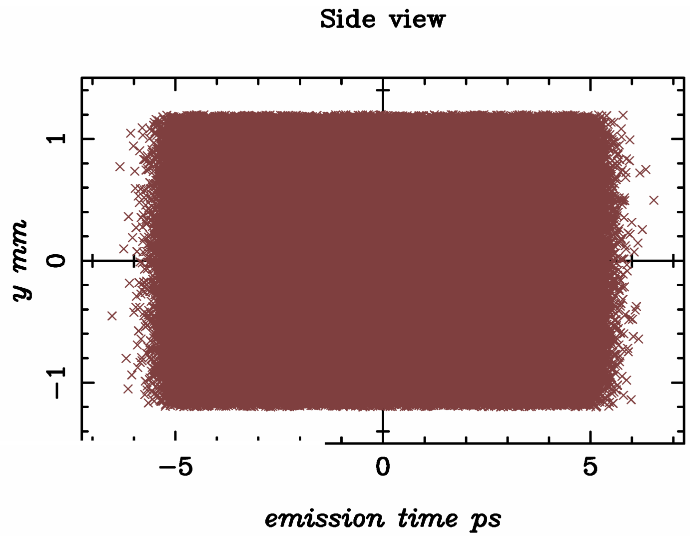
At cathode

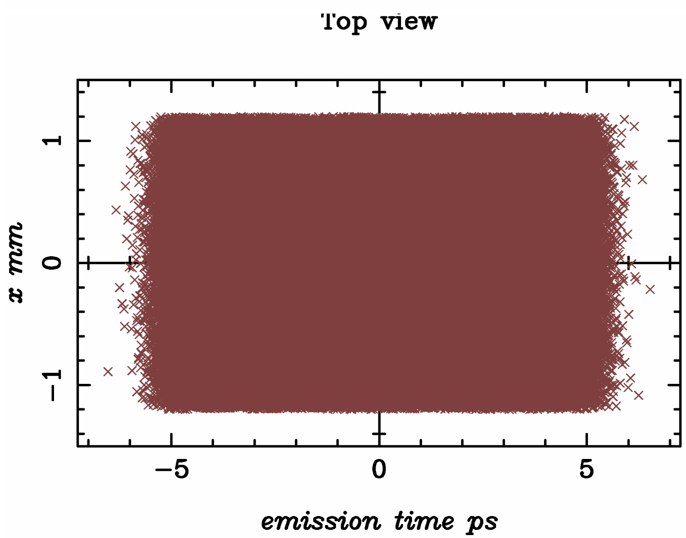


ASTRA Simulation for LCLS Injector

At cathode







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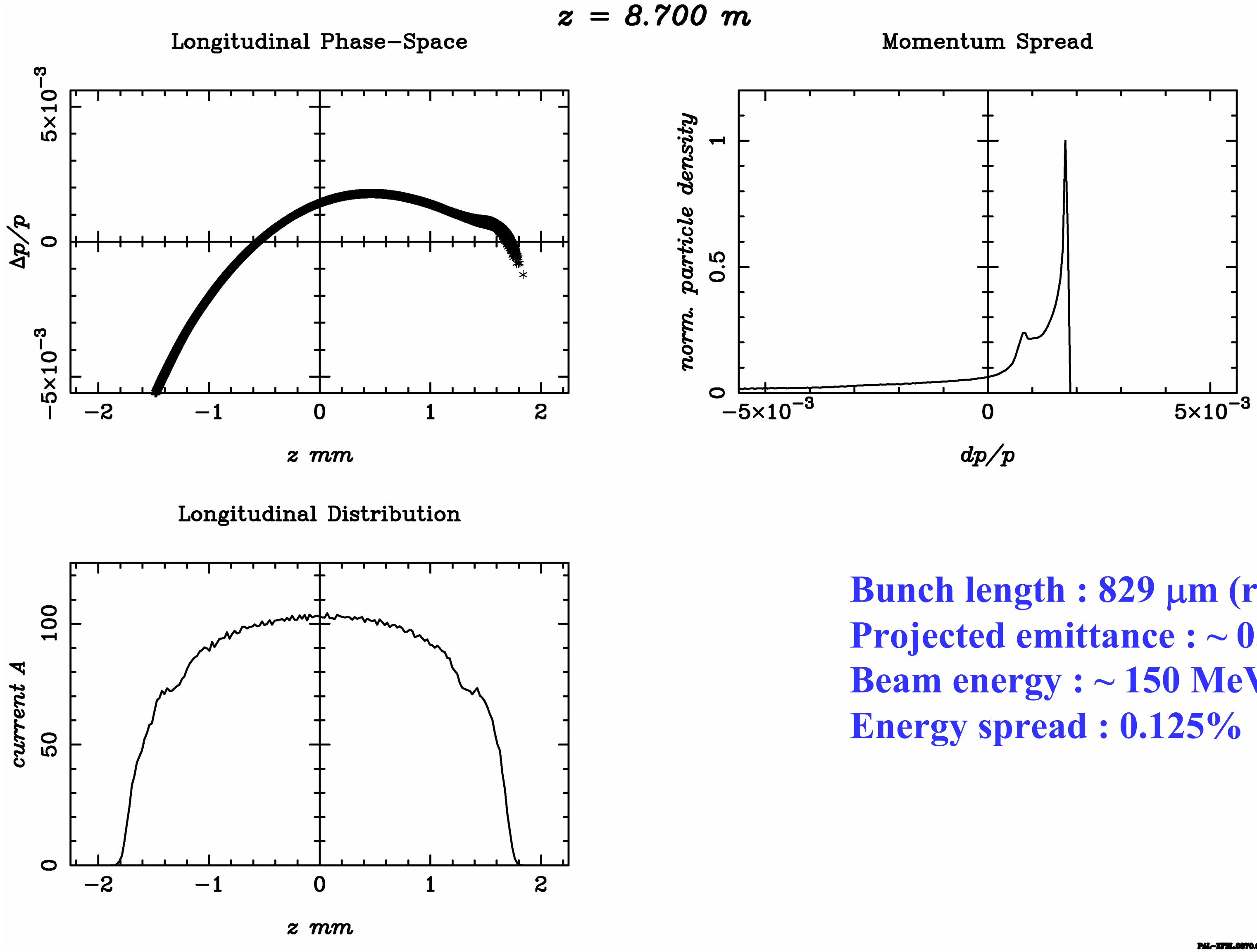
ASTRA Simulation for LCLS Injector

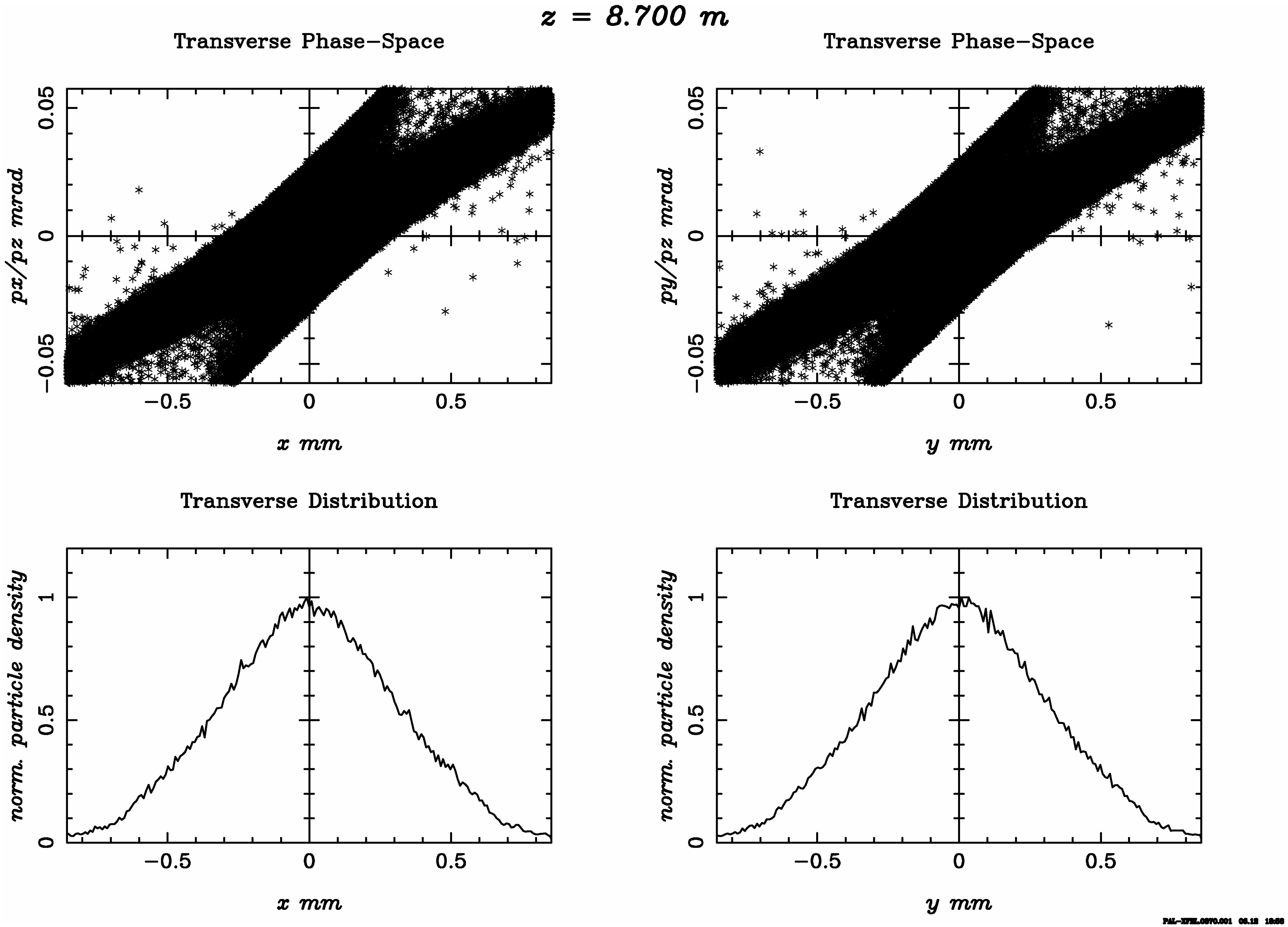
At the end of injector (X1AB) 8.7 m downstream : Longitudinal phase space



Bunch length : 829 μm (rms)
Projected emittance : ~ 0.9 μm
Beam energy : ~ 150 MeV
Energy spread : 0.125%

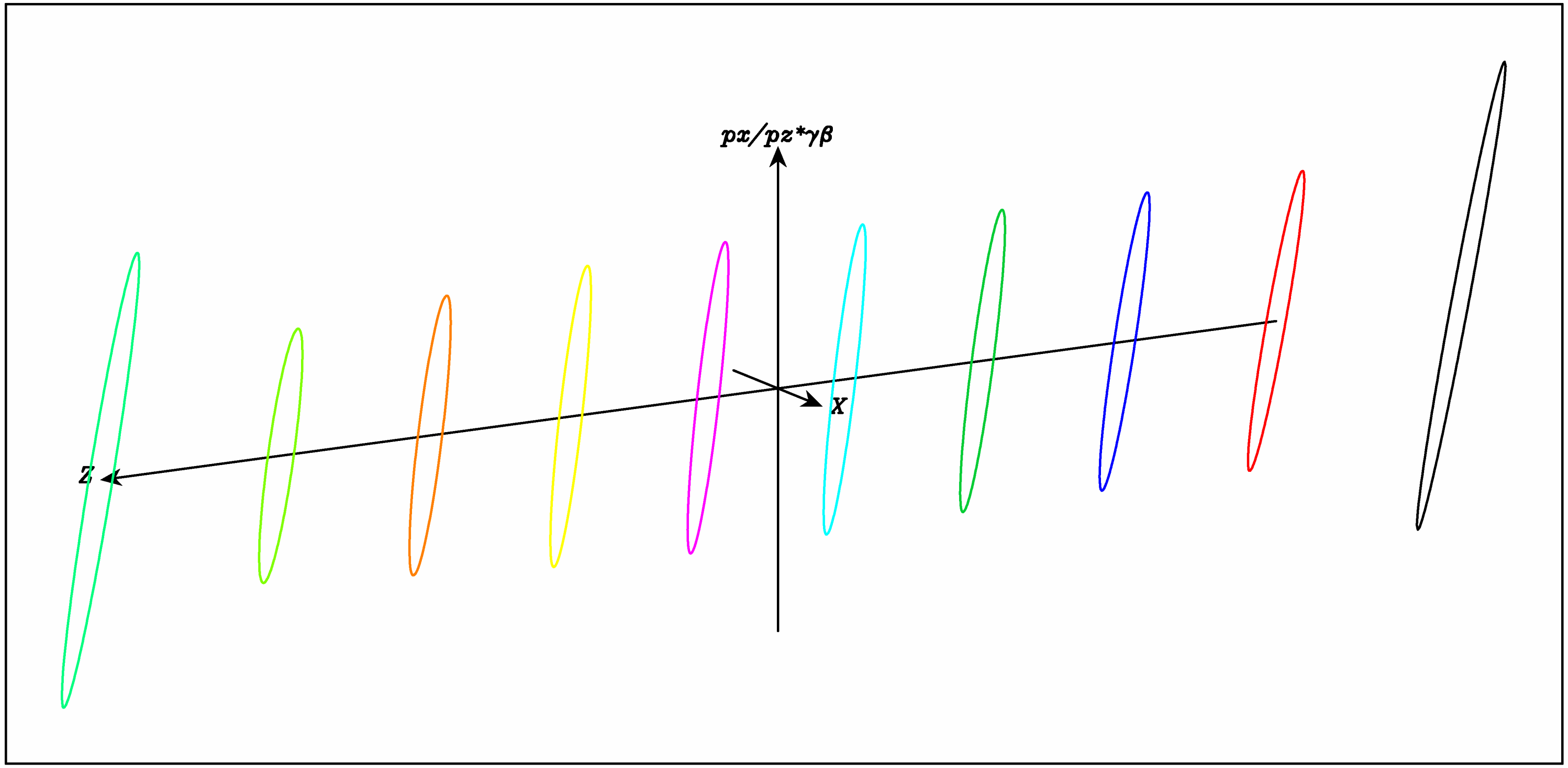
ASTRA Simulation for LCLS Injector

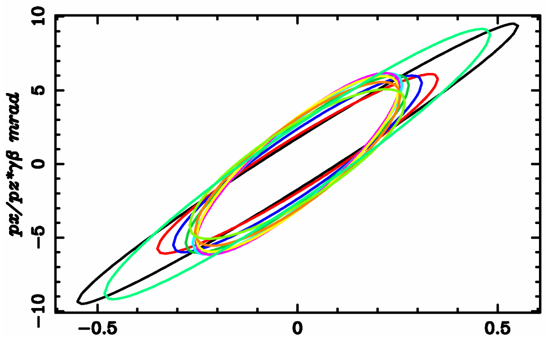
At the end of injector (X1AB) 8.7 m downstream : Transverse phase space



ASTRA Simulation for LCLS Injector

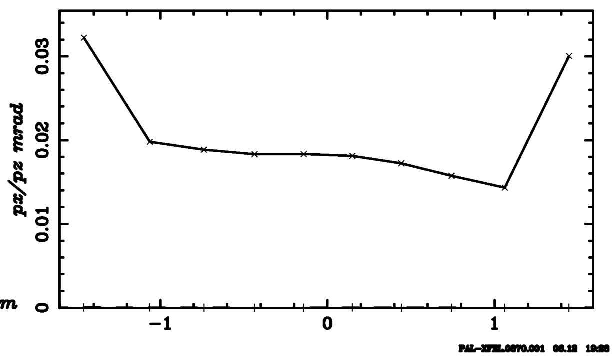
At the end of injector (X1AB) 8.7 m downstream : Slice emittances





Slice	z pos mm	x emit πmradmm	px/pz corr mrad
1	−1.5	0.96	3.22E−02
2	−1.1	0.68	1.98E−02
3	−0.74	0.74	1.89E−02
4	−0.44	0.77	1.83E−02
5	−0.14	0.79	1.83E−02
6	0.15	0.80	1.81E−02
7	0.44	0.80	1.72E−02
8	0.74	0.80	1.57E−02
9	1.1	0.77	1.43E−02
10	1.4	1.3	3.01E−02

Average norm. emittance: 0.84 πmradmm



LSC & CSR Microbunching Instability

by **longitudinal space charge force** (LSC) in the drift & linac
by **coherent synchrotron radiation** (CSR) in the bunch compressor
by the **geometric wakefields** in Linac

Initial current density modulation → **Induced energy modulation**

$dz_f = dz_i + R_{56}(dE/E)_i$ in BC

Amplified current density modulation

Slice emittance
Projected emittance
Slice energy spread
Growth !!!

$$Gain = \left| \frac{\text{Normalized amp. of current density}_2}{\text{Normalized amp. of current denisty}_1} \right|$$

Lattice Design Concepts for PAL-XFEL

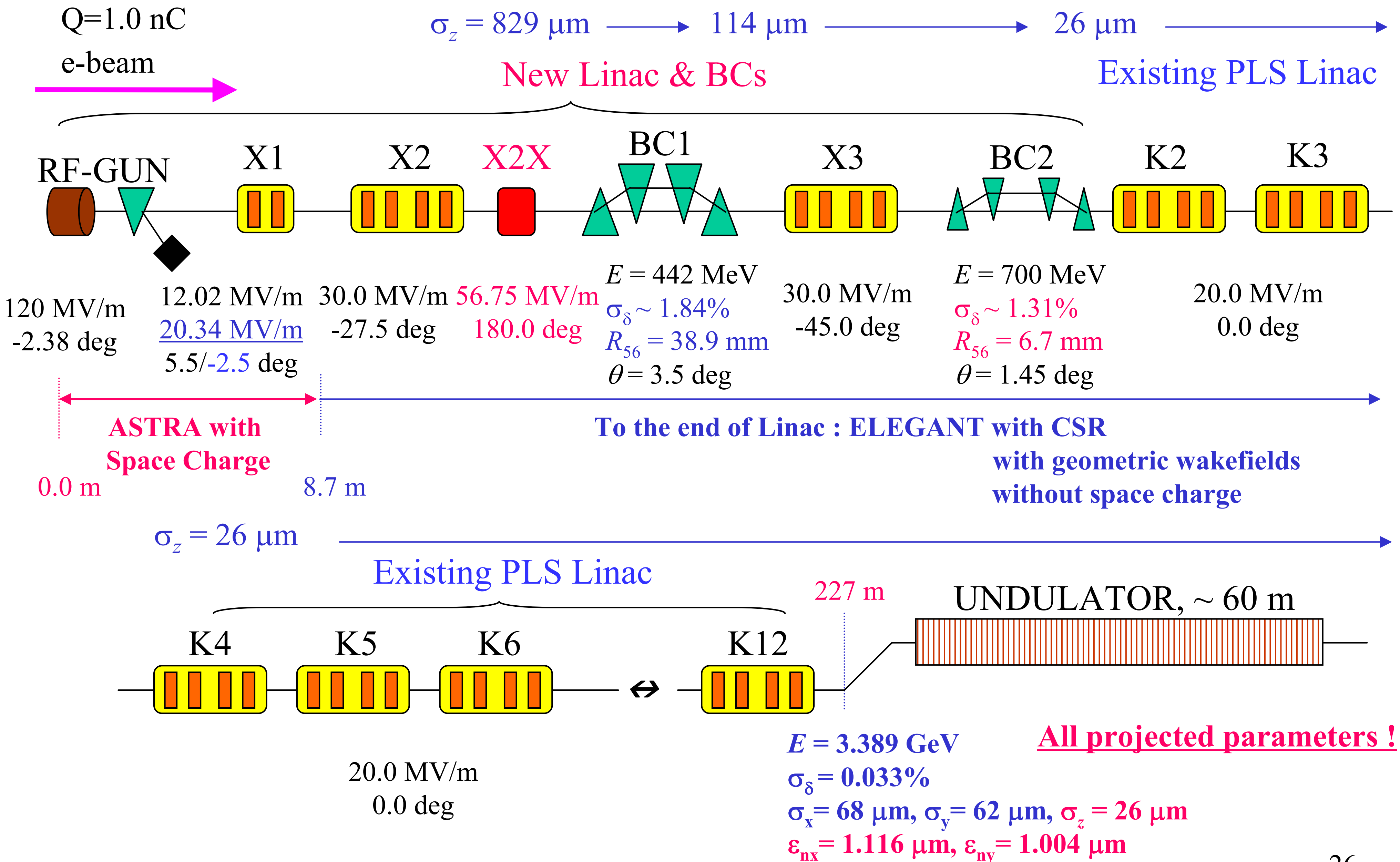
❑ Reducing projected emittance growth due to CSR & Chromatic Effects

- Keeping somewhat large energy spread at BCs by putting BCs at a lower energy
- Reducing QM length around BCs to reduce chromatic effect
- Using weaker strength chicane with a longer chicane length of ~ 15 m
- Using a longer drift space between 1st and 2nd dipoles in BCs
- Optimizing Twiss parameters around BCs
- Selecting smaller compression factor at BC2 against CSR there

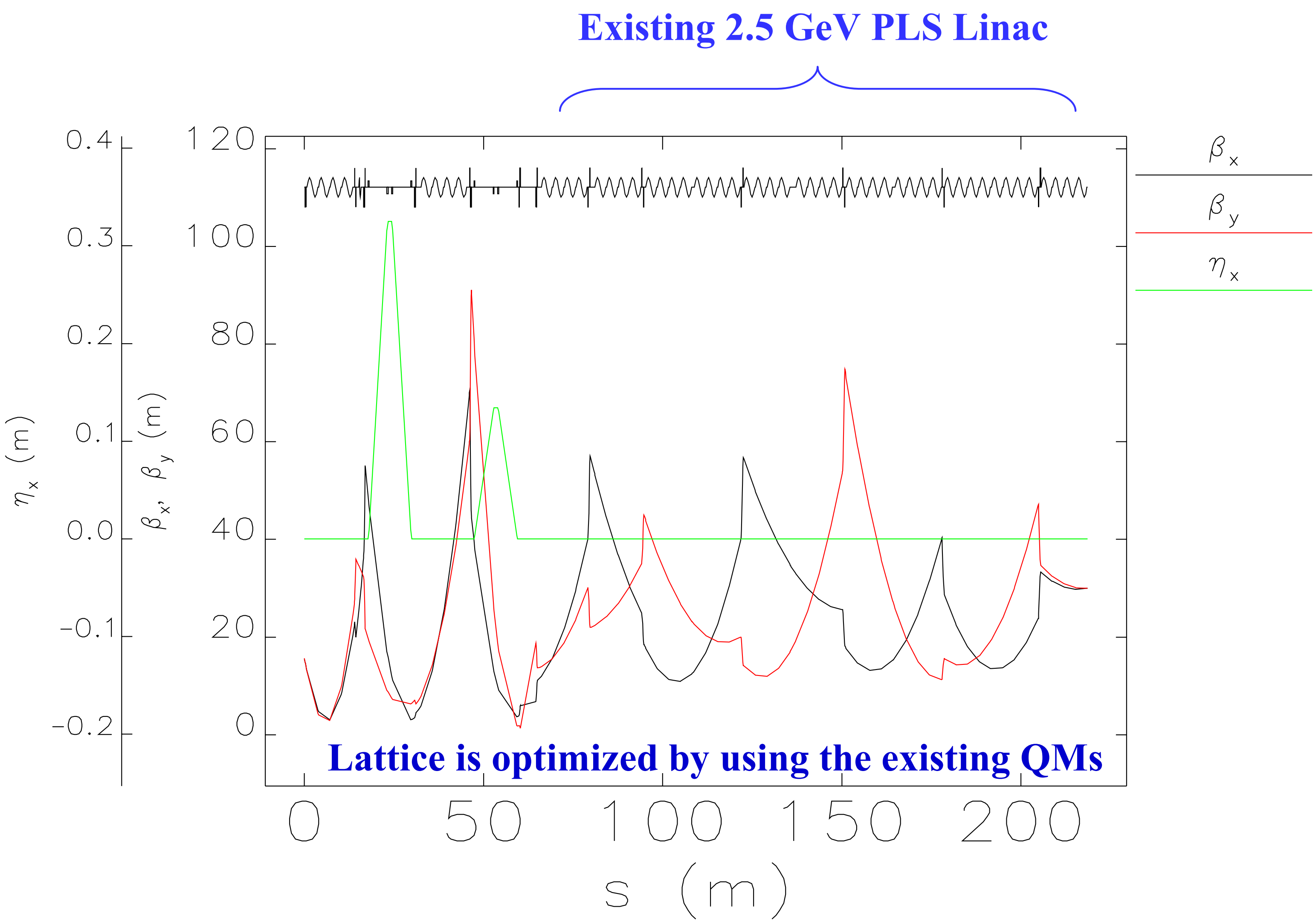
❑ Reducing Slice Parameter Growths due to the Microbunching Instability

- Use the normal 4-bends normal chicane
- Smearing the microbunching instability at BC2 by keeping large uncorrelated energy spread at BC2 with only one acceleration column between BC1 and BC2

New Layout for PAL XFEL - 05DEC03 Version



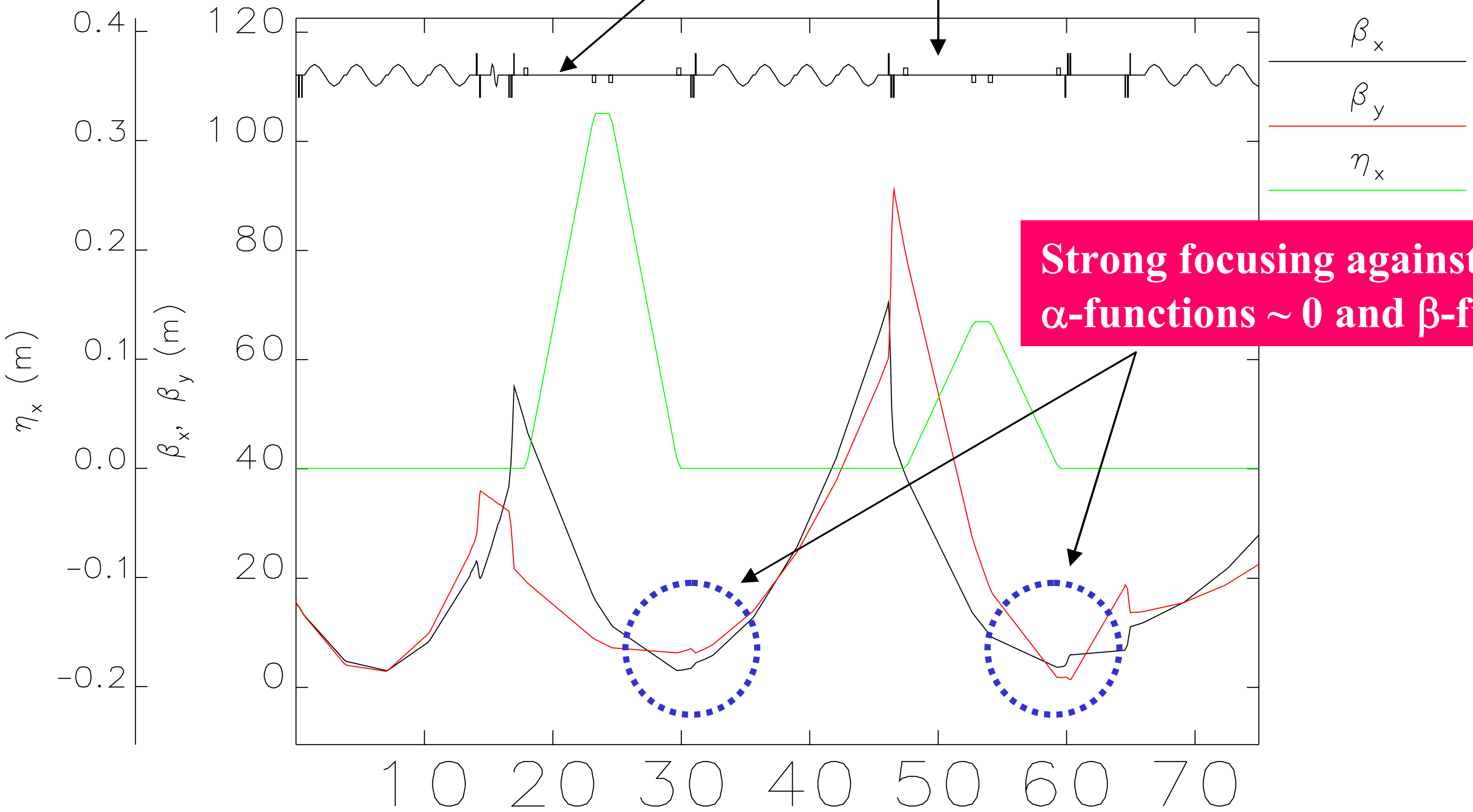
Twiss Parameters in Linac for PAL-XFEL



In the near future, Twiss parameters in the existing linac will be re-optimized !!!

Twiss Parameters in Linac for PAL-XFEL

Reduced dipole strengths with long chicane length

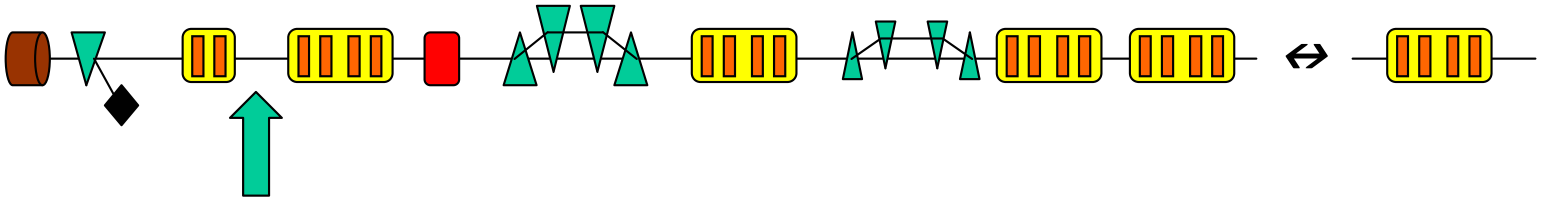


Strong focusing against CSR
α-functions ~ 0 and β-functions ~ 3

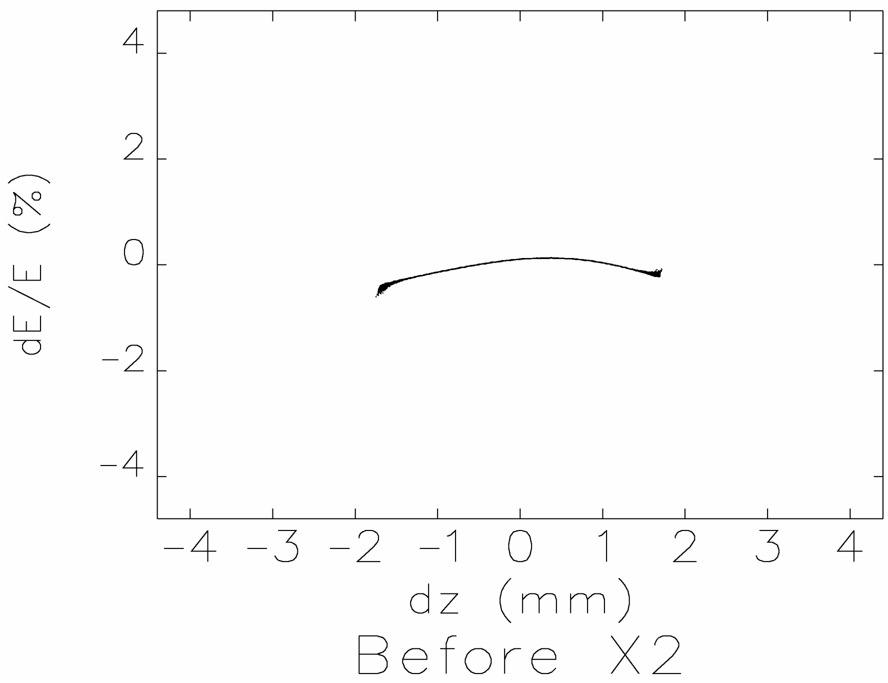
$$\frac{\varepsilon}{\varepsilon_0} \approx \sqrt{1+\frac{(0.22)^2}{36}\frac{r_e^2 N^2}{\gamma\varepsilon_N\beta}\left(\frac{|\theta|^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha^2\right)+9\beta^2+6\alpha\beta L_B\right]}$$

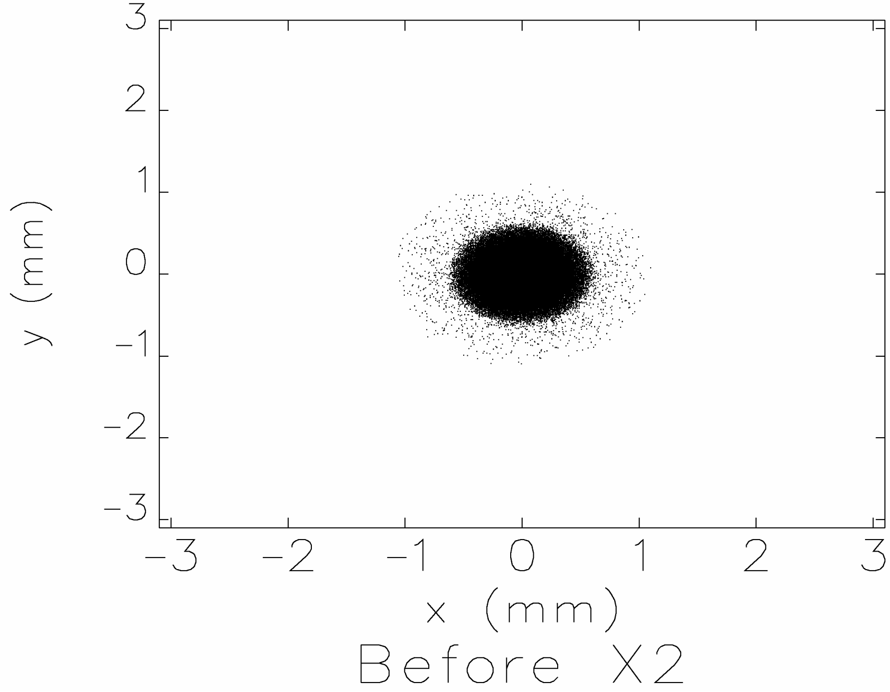
Lattice optimization to minimize this term

PAL XFEL : Phase Spaces - Before X2



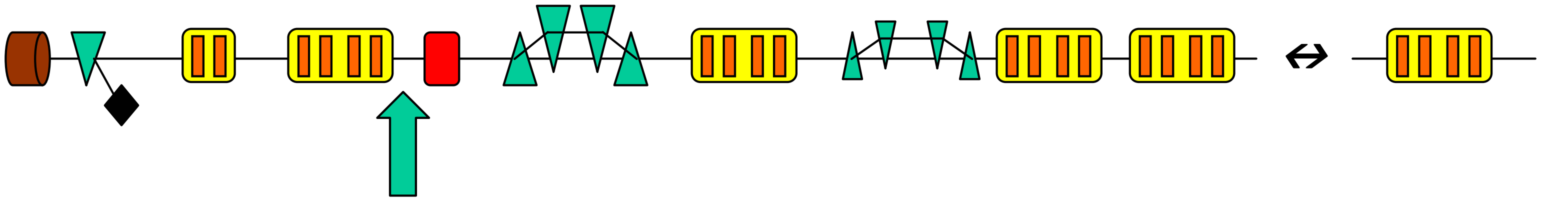
Simulated Particles = 200000





***E* = 149.4 MeV**
σ_δ = 0.125%
σ_x = 219 µm, σ_y = 222 µm, σ_z = 829 µm
ε_{nx} = 0.909 µm, ε_{ny} = 0.925 µm

PAL XFEL : Phase Spaces - After X2



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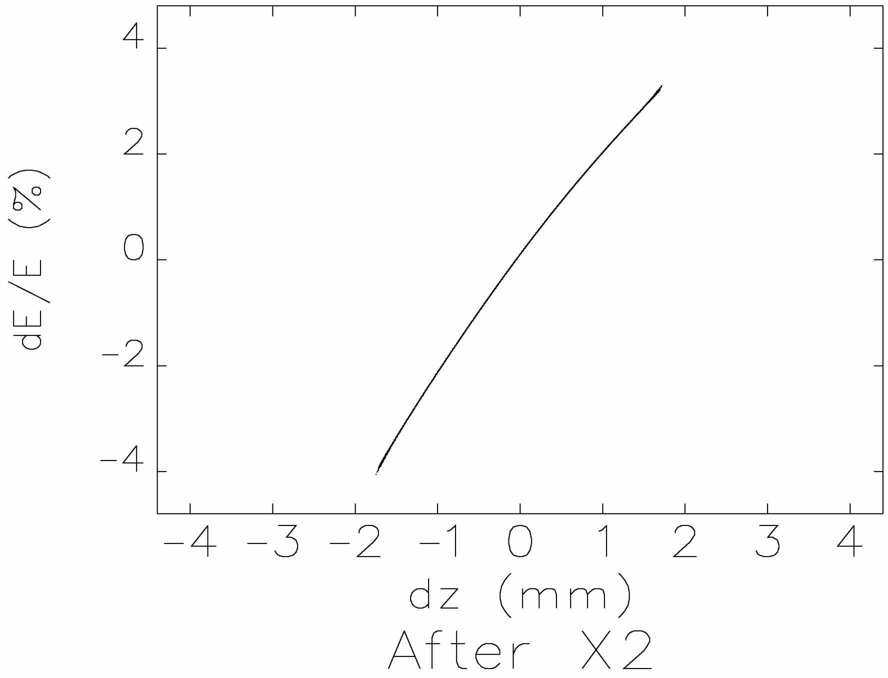
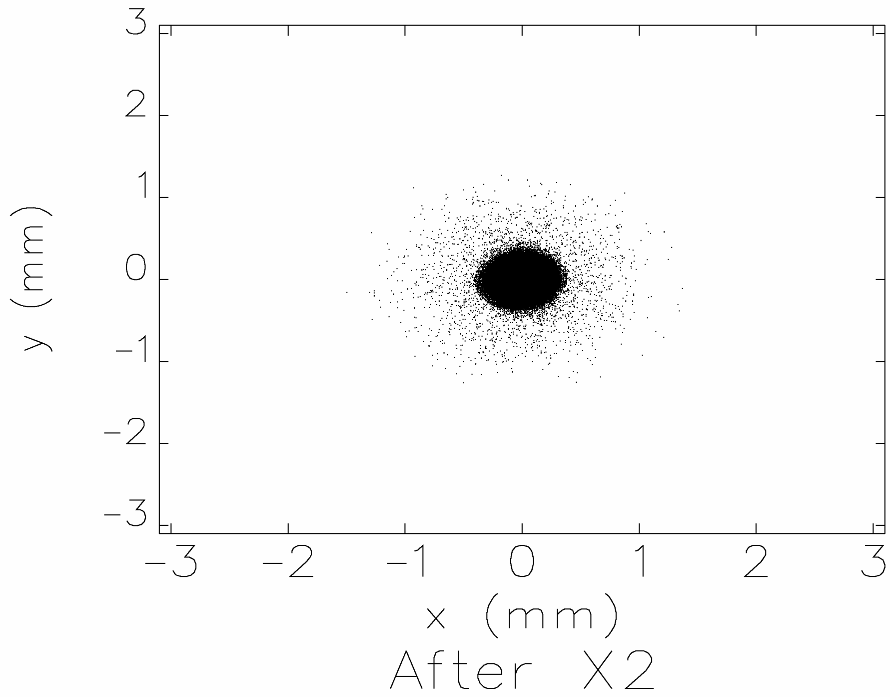
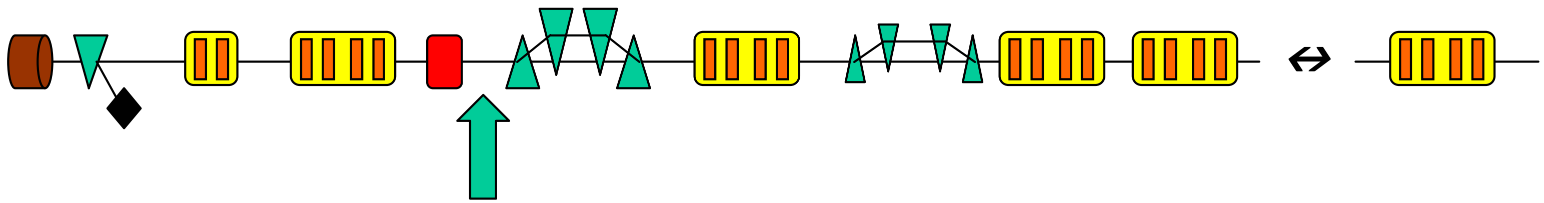


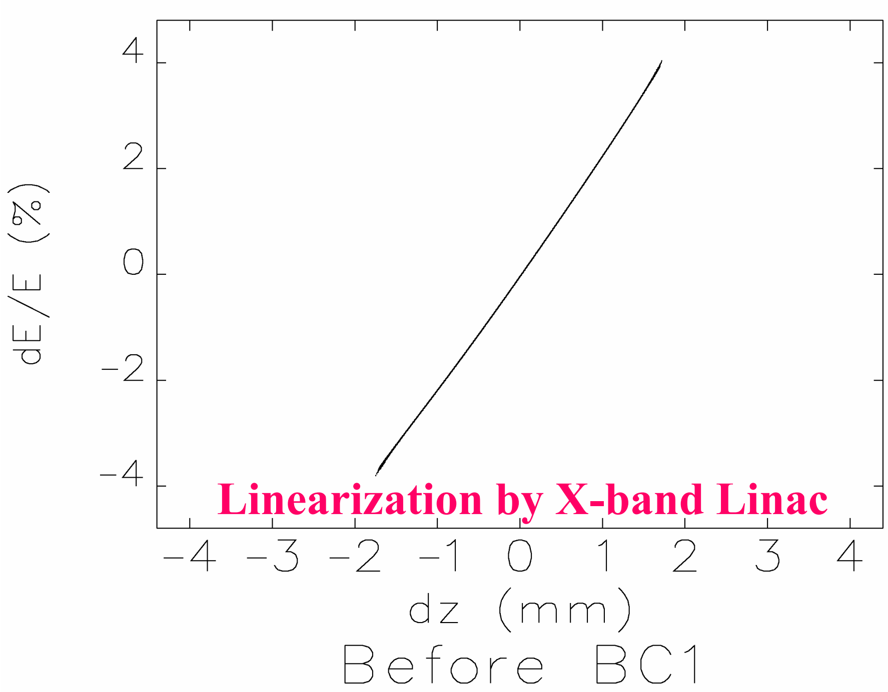


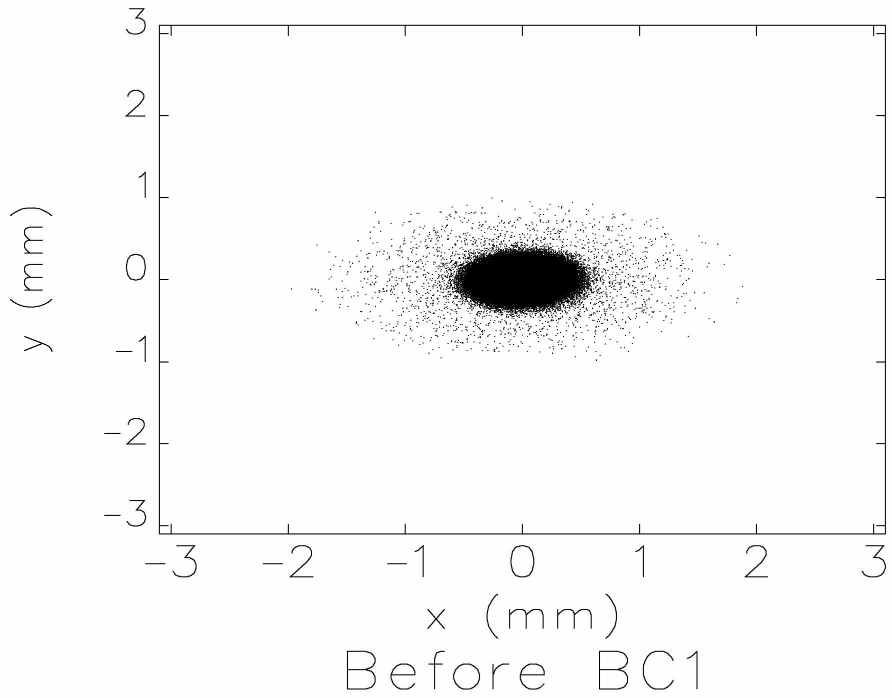
E = 475.3 MeV
σ_δ = 1.726%
σ_x = 143 μm, σ_y = 158 μm, σ_z = 829 μm
ε_{nx} = 0.910 μm, ε_{ny} = 0.926 μm

PAL XFEL : Phase Spaces - Before BC1



Simulated Particles = 200000





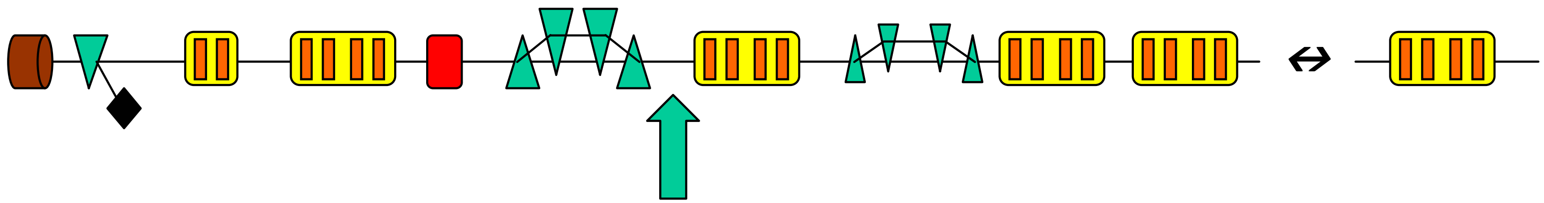
E = 441.5 MeV

σ_δ = 1.835%

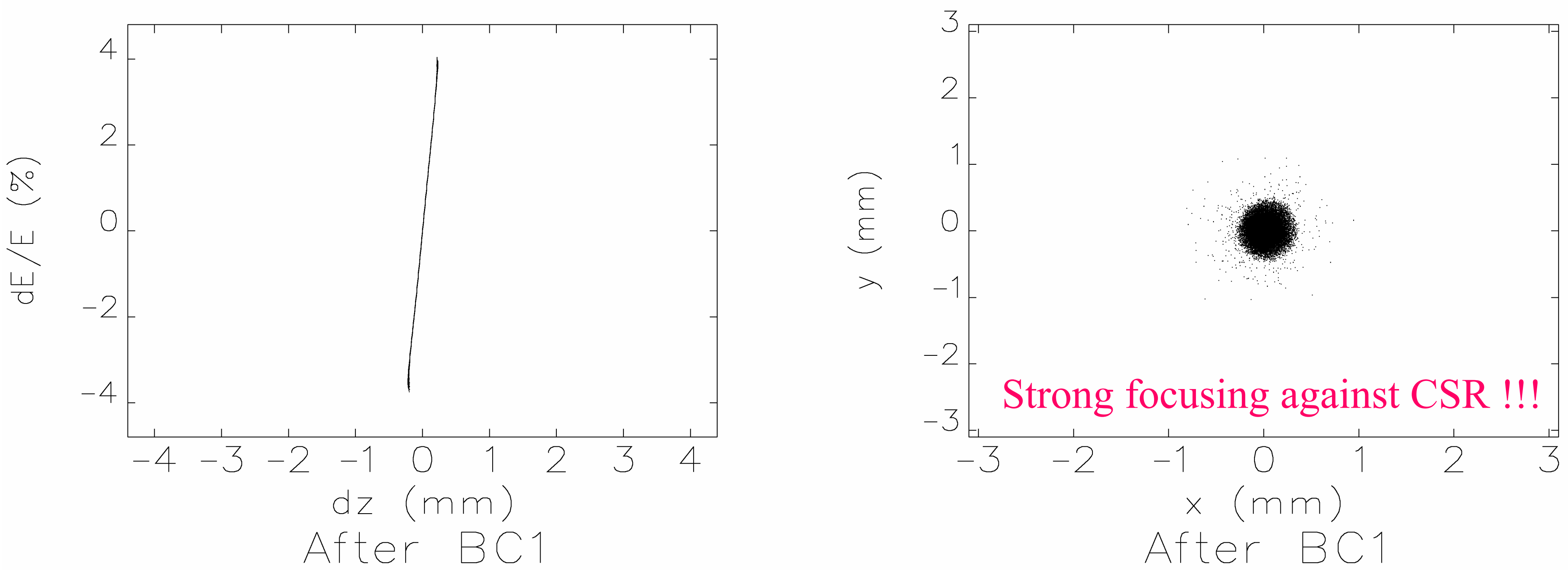
σ_x = 230 μm, σ_y = 147 μm, σ_z = 829 μm

ε_{nx} = 0.953 μm, ε_{ny} = 0.945 μm

PAL XFEL : Phase Spaces - After BC1



Simulated Particles = 200000



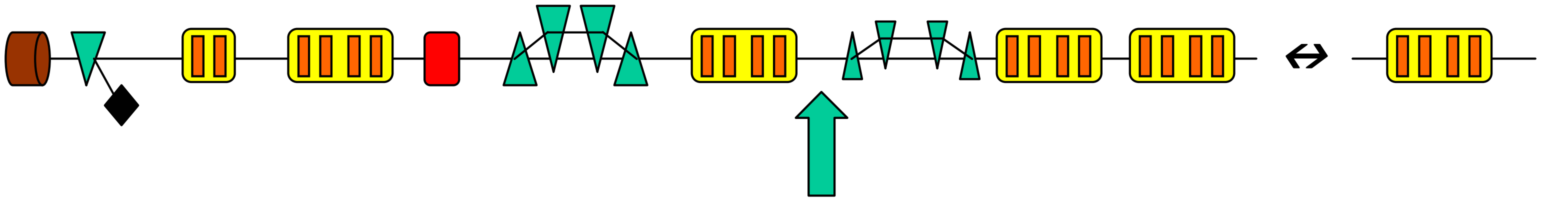
E **= 441.3 MeV**

σ_δ **= 1.819%**

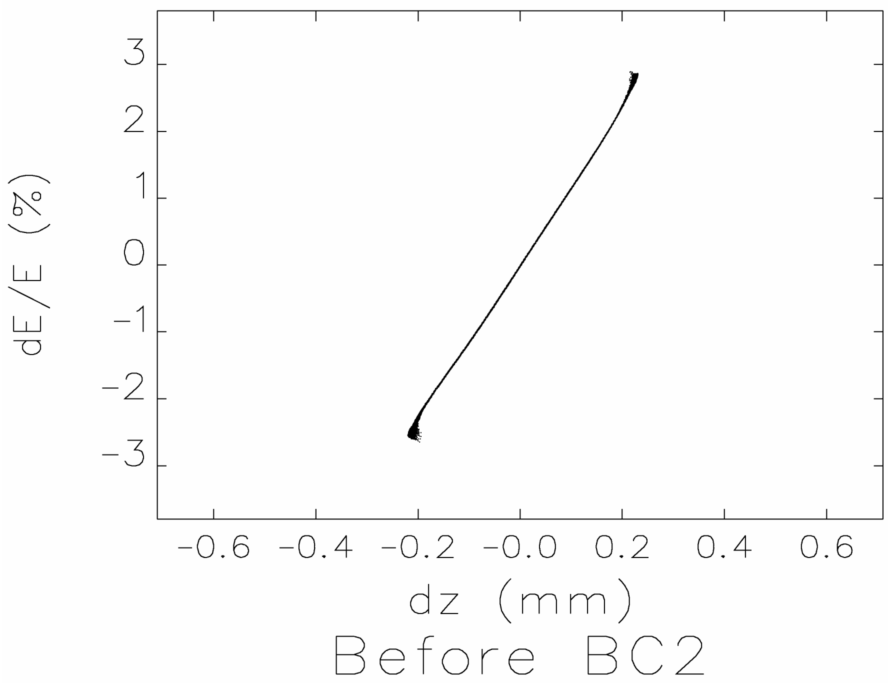
σ_x **= 61.7 μm,** σ_y **= 85.6 μm,** σ_z **= 114 μm**

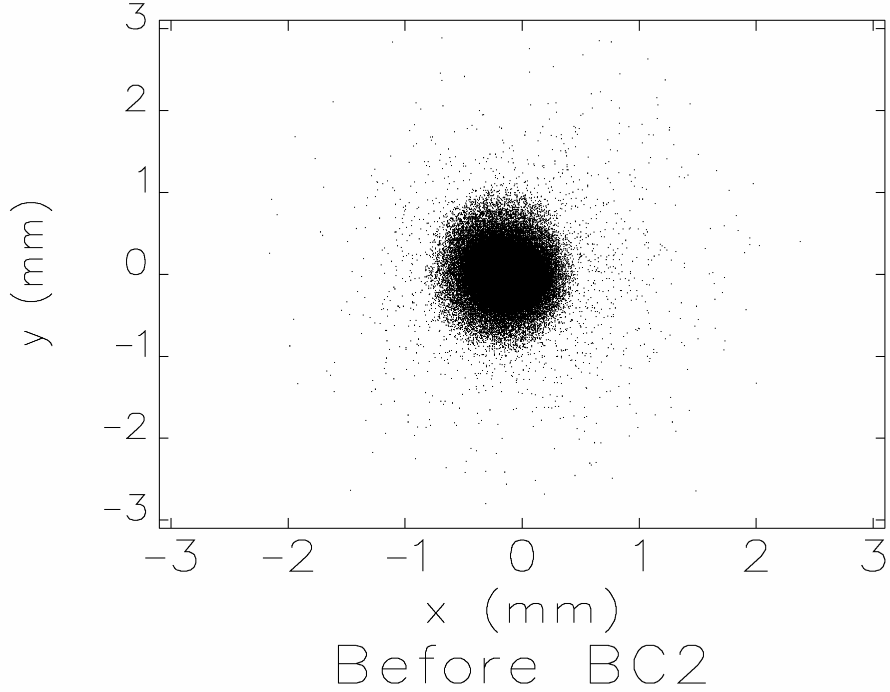
ε_{nx} **= 1.012 μm,** ε_{ny} **= 0.946 μm**

PAL XFEL : Phase Spaces - Before BC2



Simulated Particles = 200000





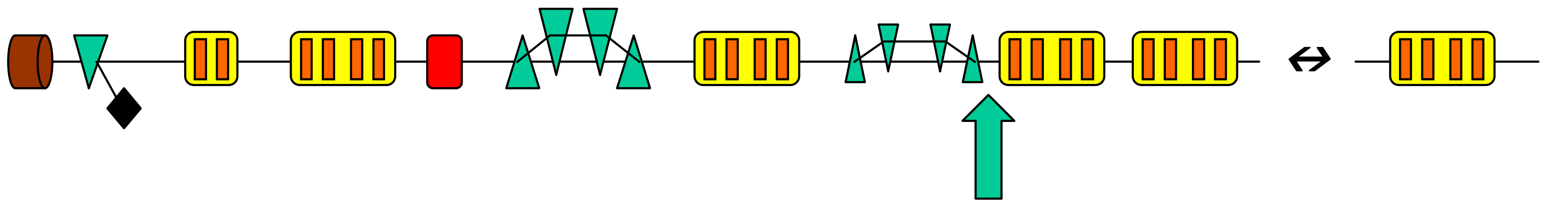
E = 700.8 MeV

σ_δ = 1.310%

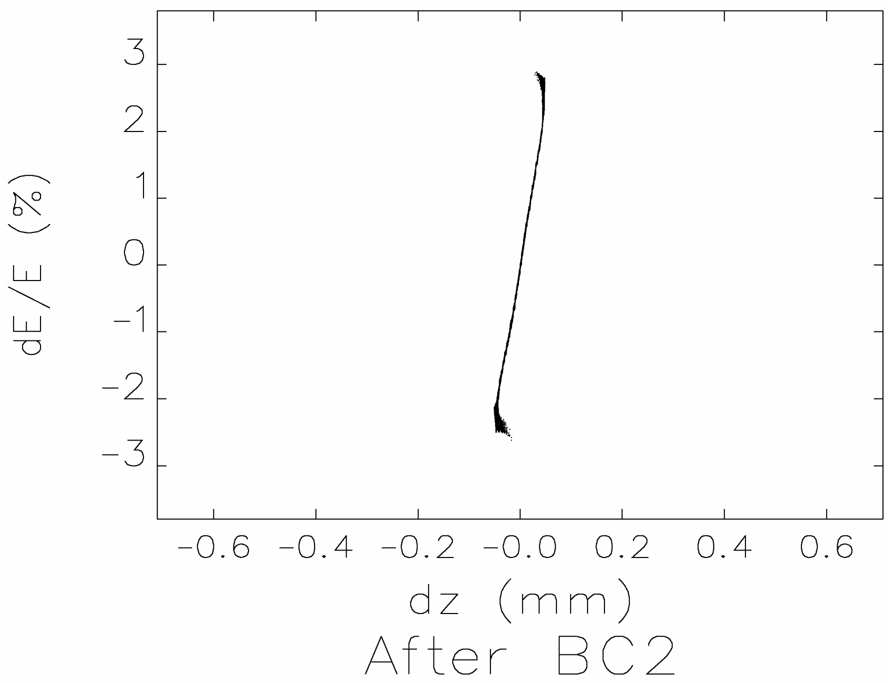
σ_x = 174 µm, σ_y = 240 µm, σ_z = 114 µm

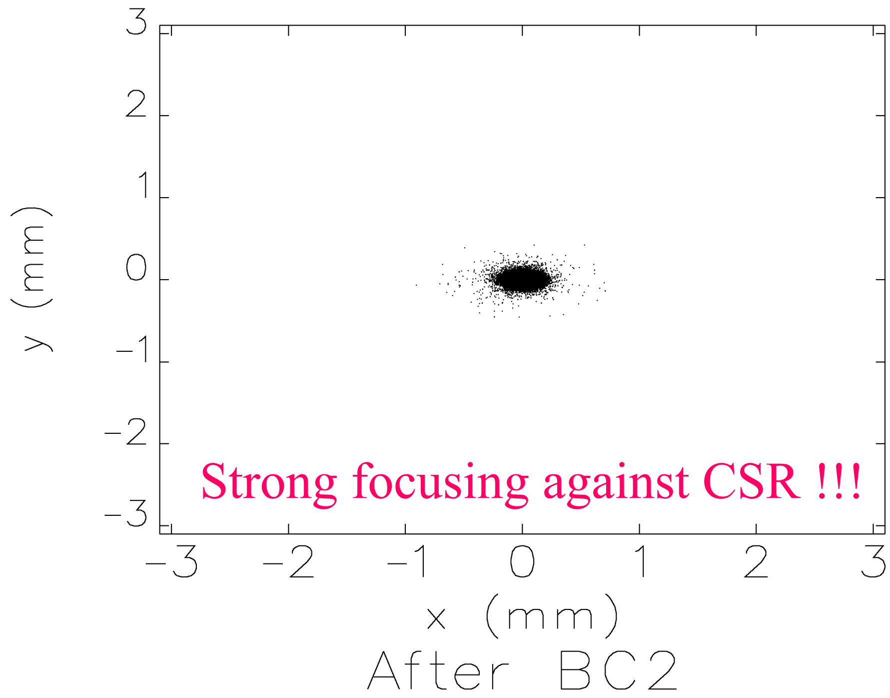
ε_{nx} = 1.069 µm, ε_{ny} = 0.990 µm

PAL XFEL : Phase Spaces - After BC2



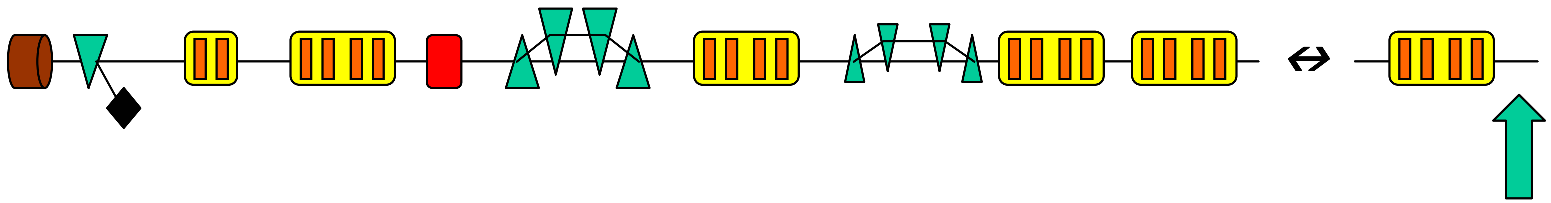
Simulated Particles = 200000



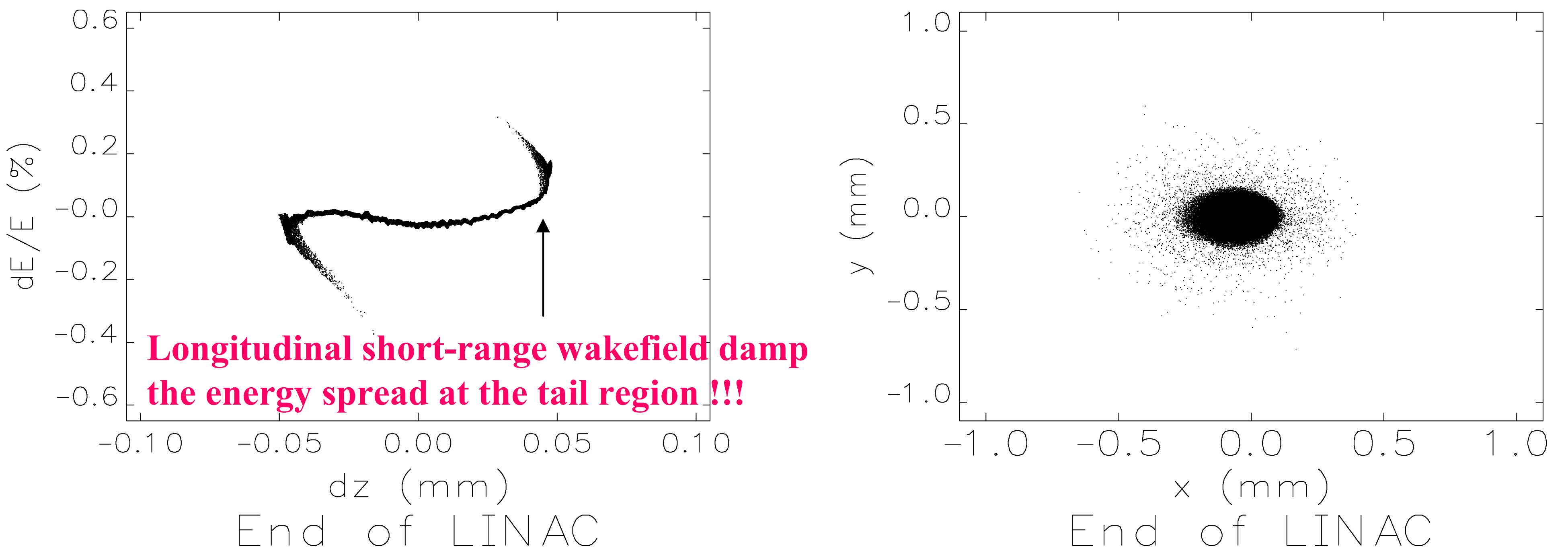


E **= 699.9 MeV**
$\sigma_\delta = 1.267\%$
$\sigma_x = 55\ \mu m$, $\sigma_y = 36.8\ \mu m$, $\sigma_z = 26\ \mu m$
$\varepsilon_{nx} = 1.090\ \mu m$, $\varepsilon_{ny} = 0.990\ \mu m$

PAL XFEL : Phase Spaces - End of Linac



Simulated Particles = 200000



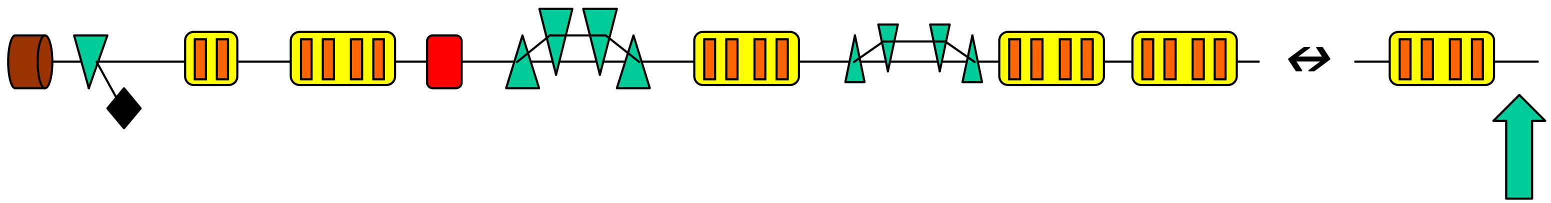
E **= 3.389 GeV**

$\sigma_\delta = 0.033\%$

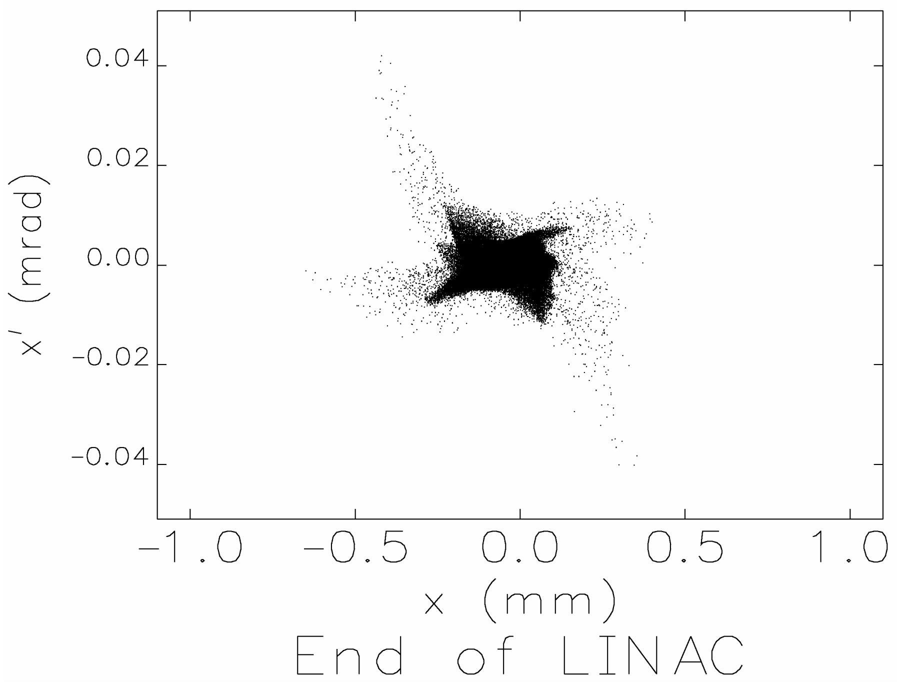
$\sigma_x = 68.1\ \mu m$, $\sigma_y = 61.9\ \mu m$, $\sigma_z = 26\ \mu m$

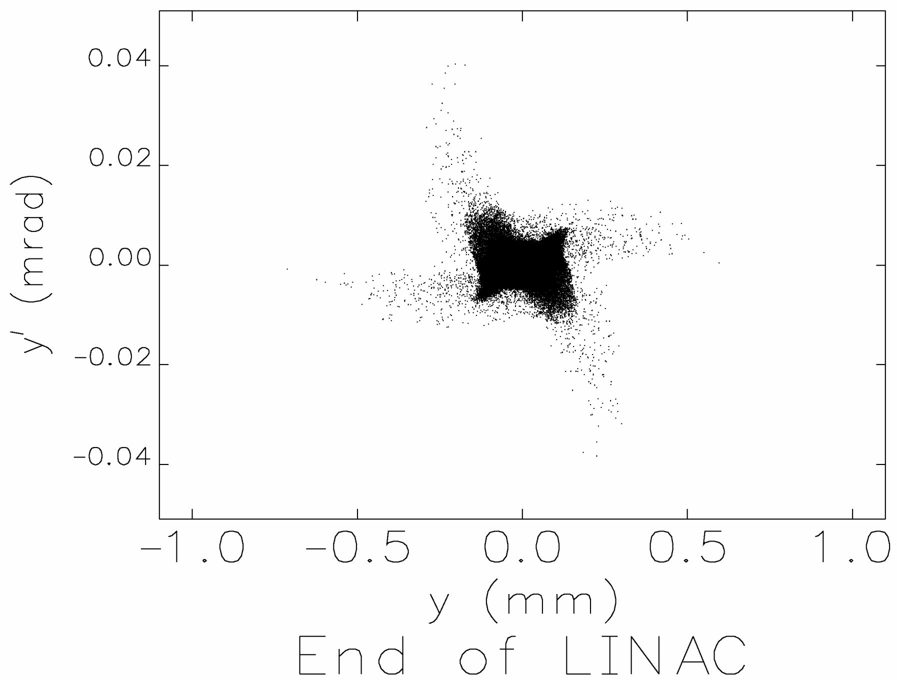
$\varepsilon_{nx} = 1.116\ \mu m$, $\varepsilon_{ny} = 1.004\ \mu m$

PAL XFEL : Phase Spaces - End of Linac



Simulated Particles = 200000





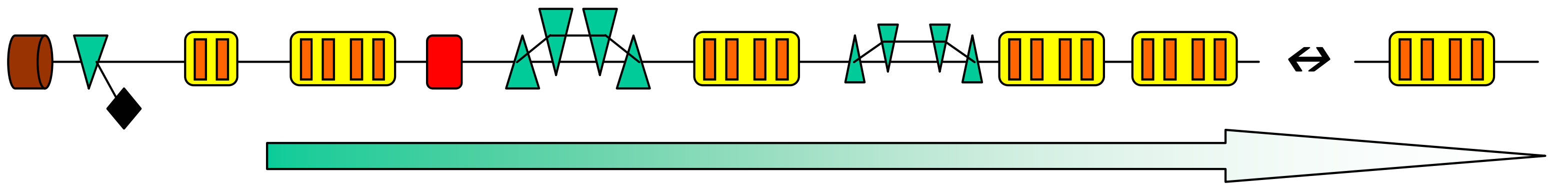
E = 3.389 GeV

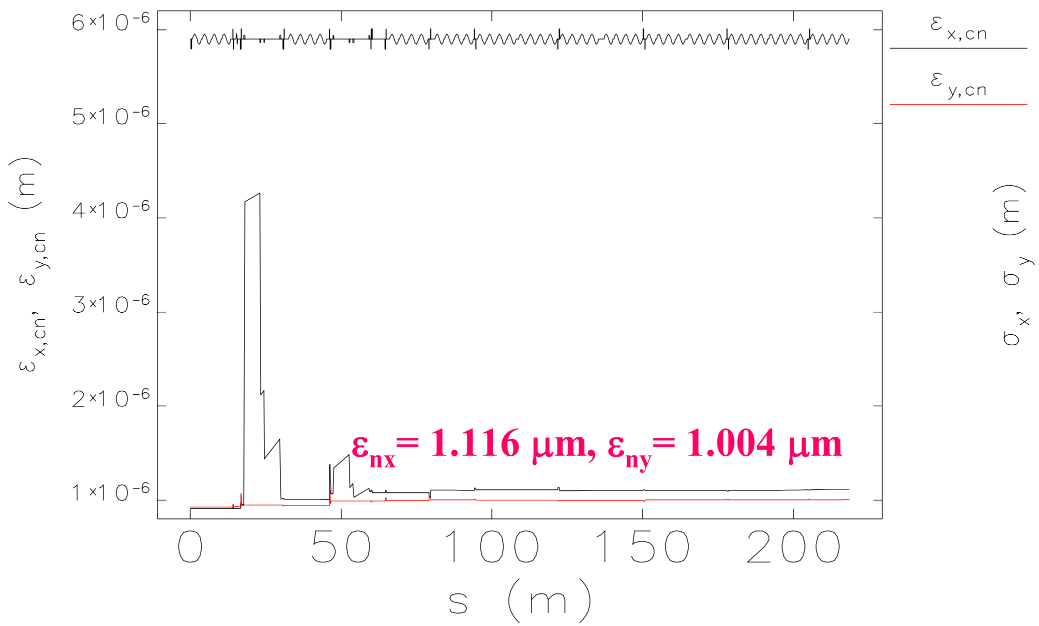
σ_δ = 0.033%

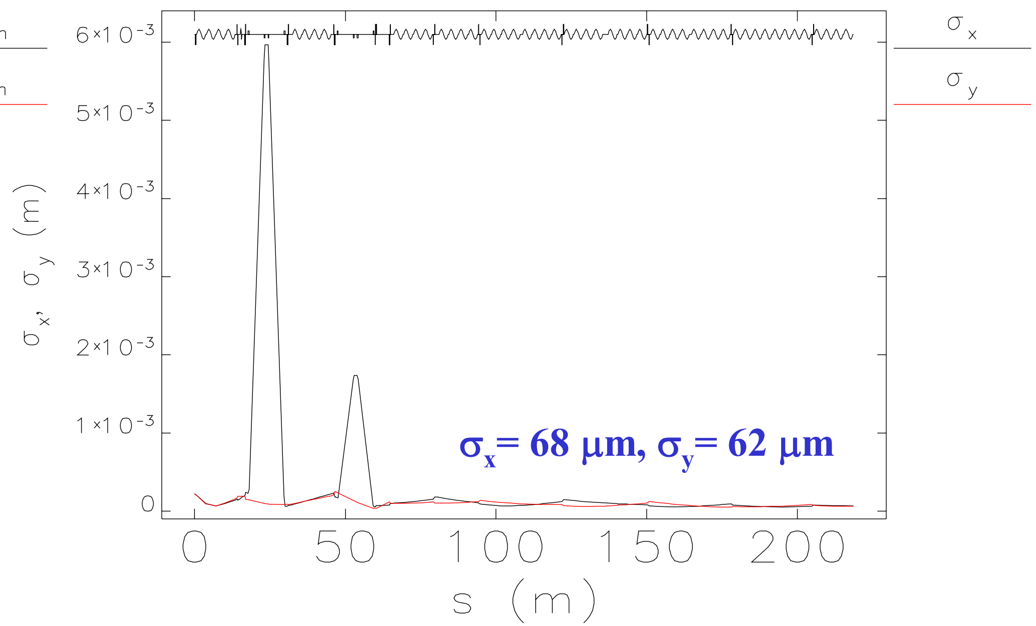
σ_x = 68.1 µm, σ_y = 61.9 µm, σ_z = 26 µm

ε_{nx} = 1.116 µm, ε_{ny} = 1.004 µm

PAL XFEL : Projected Parameters







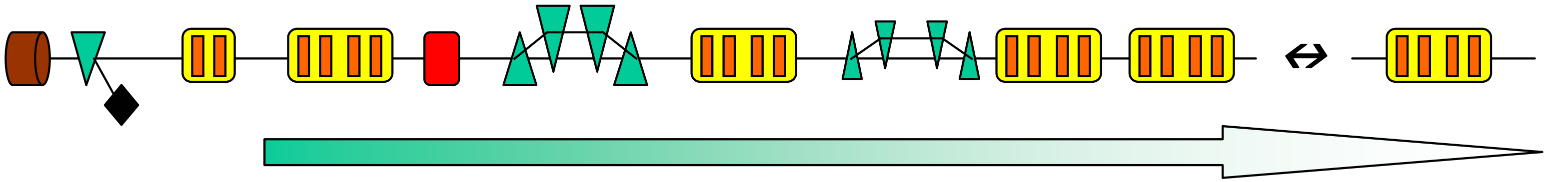
E = 3.389 GeV

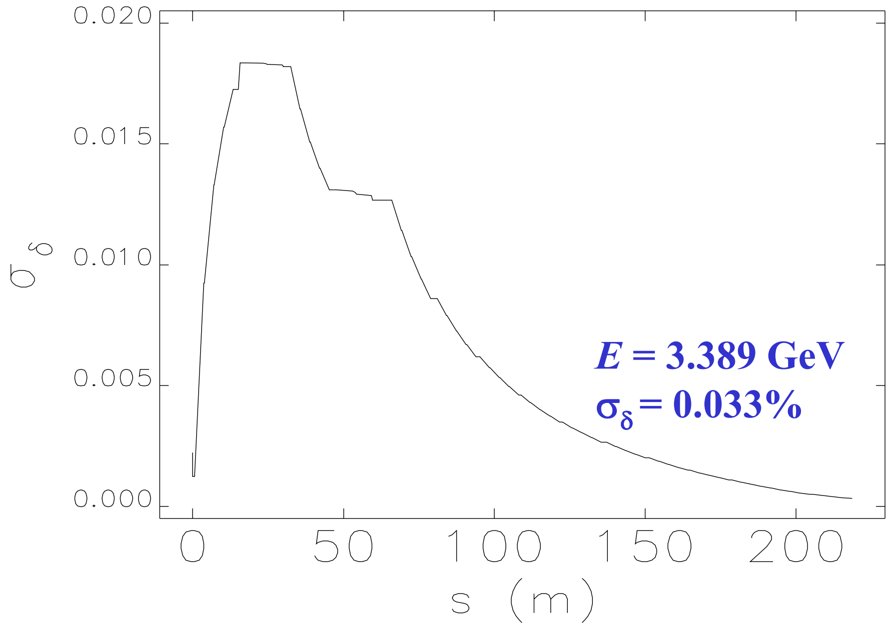
σ_δ = 0.033%

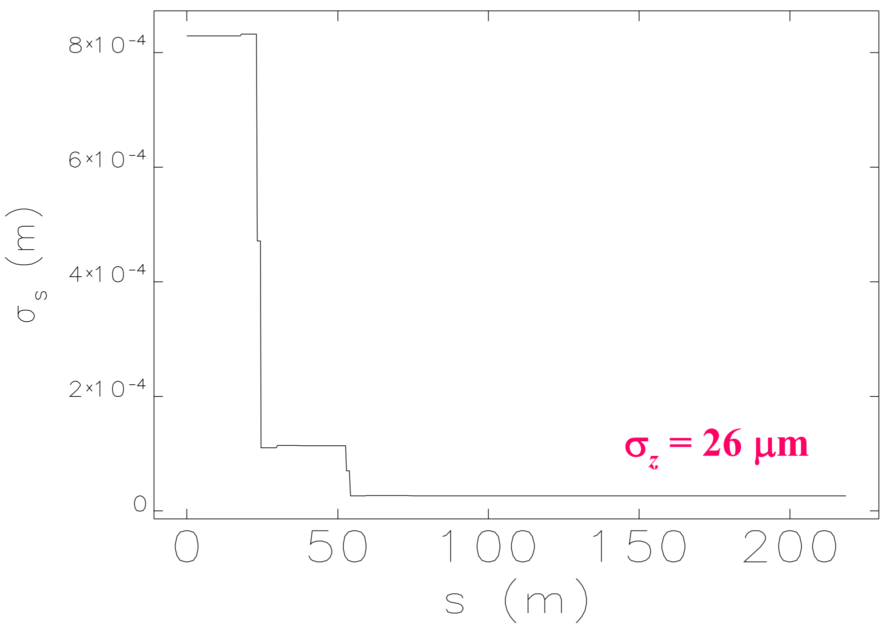
σ_x = 68.1 μm, σ_y = 61.9 μm, σ_z = 26 μm

ε_{nx} = 1.116 μm, ε_{ny} = 1.004 μm

PAL XFEL : Projected Parameters

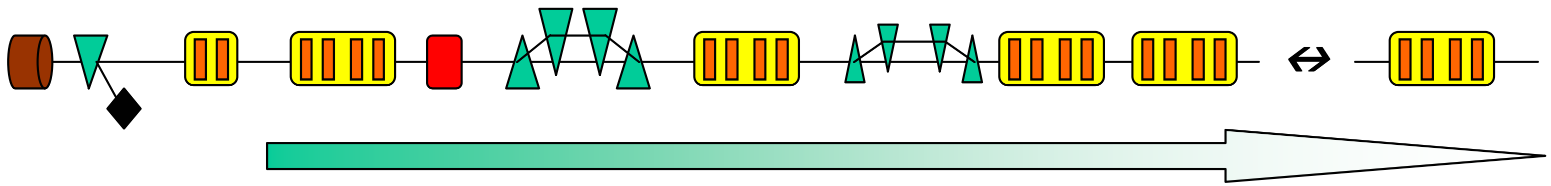


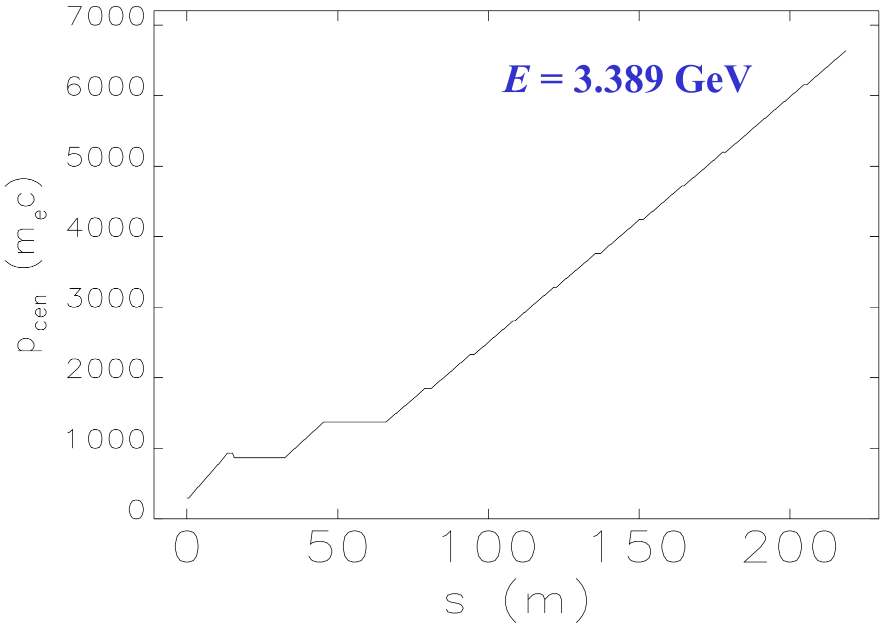


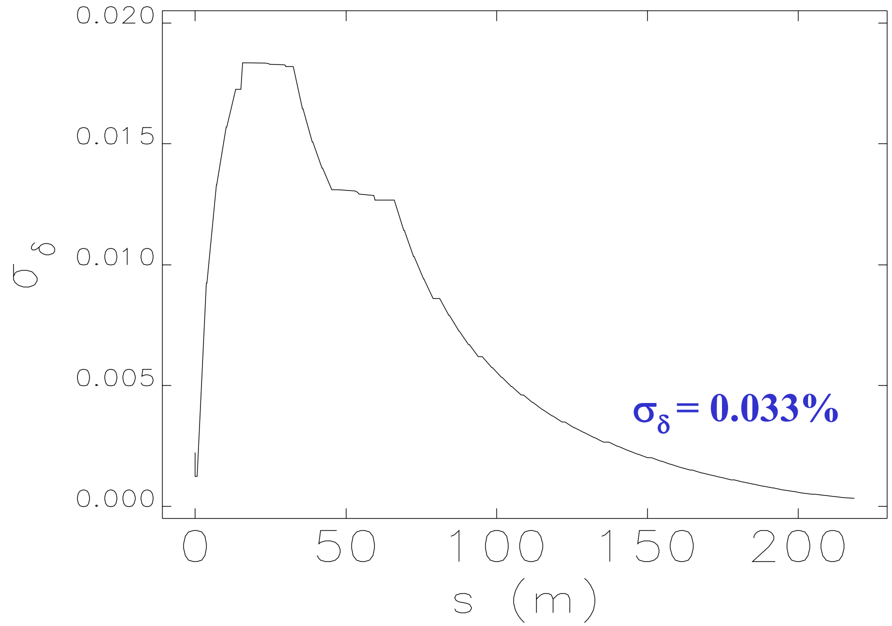


E = 3.389 GeV
σ_δ = 0.033%
σ_x= 68.1 μm, σ_y= 61.9 μm, σ_z = 26 μm
ε_{nx}= 1.116 μm, ε_{ny}= 1.004 μm

PAL XFEL : Projected Parameters

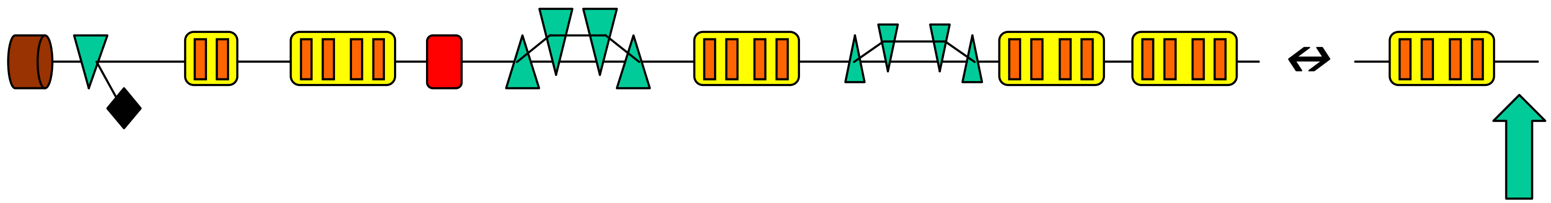


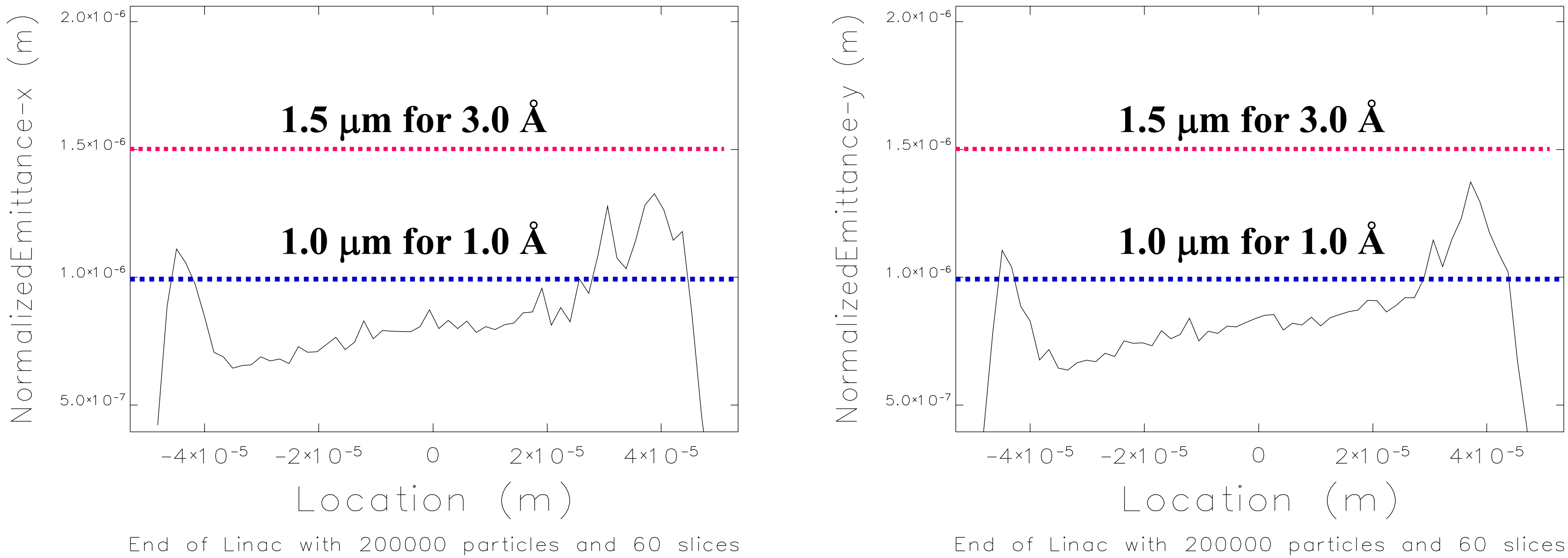




E = 3.389 GeV
σ_δ = 0.033%
σ_x = 68.1 μm, σ_y = 61.9 μm, σ_z = 26 μm
ε_{nx} = 1.116 μm, ε_{ny} = 1.004 μm

Slice Emittances at the End of PAL XFEL Linac





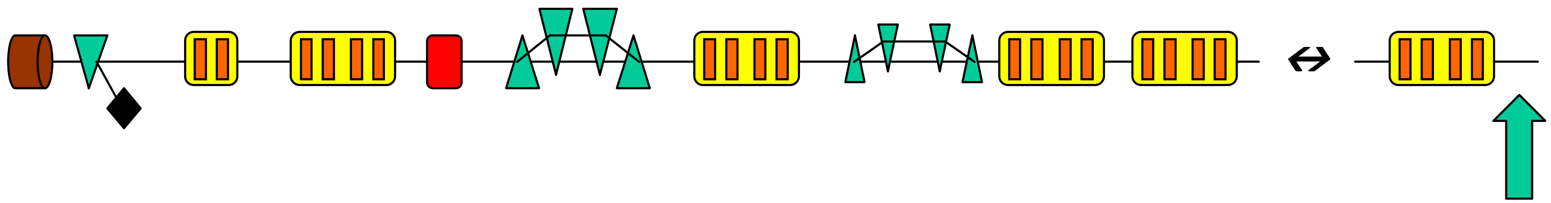
E = 3.389 GeV

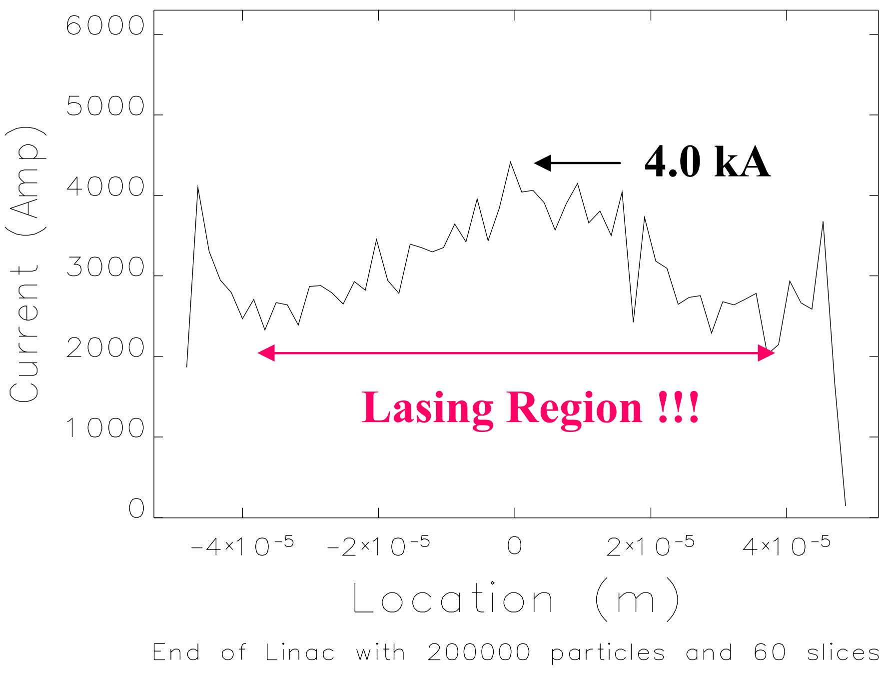
σ_δ = 0.033%

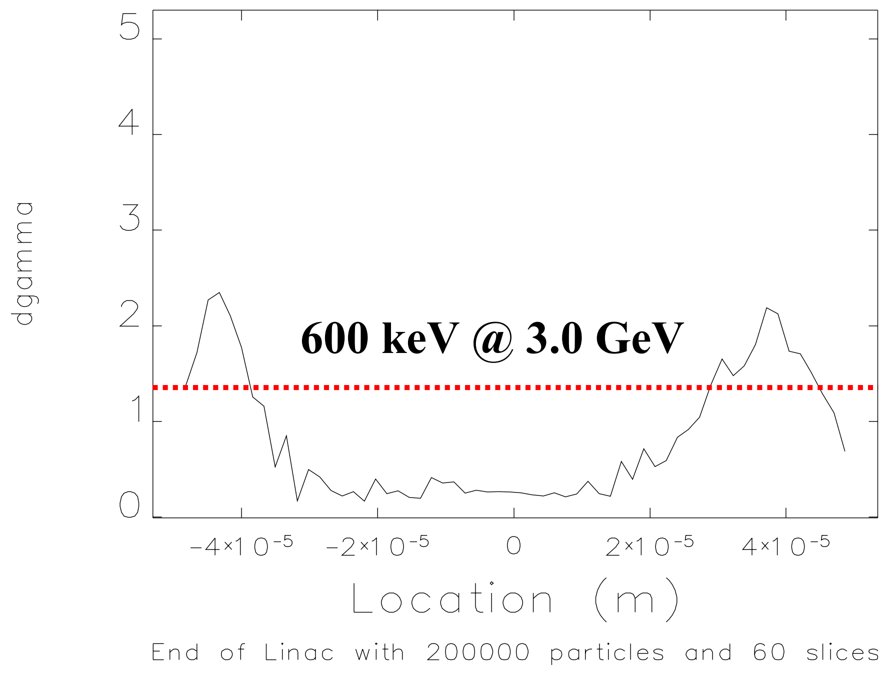
σ_x = 68.1 μm, σ_y = 61.9 μm, σ_z = 26 μm

ε_{nx} = 1.116 μm, ε_{ny} = 1.004 μm

Current & Slice Energy Spread at End of Linac





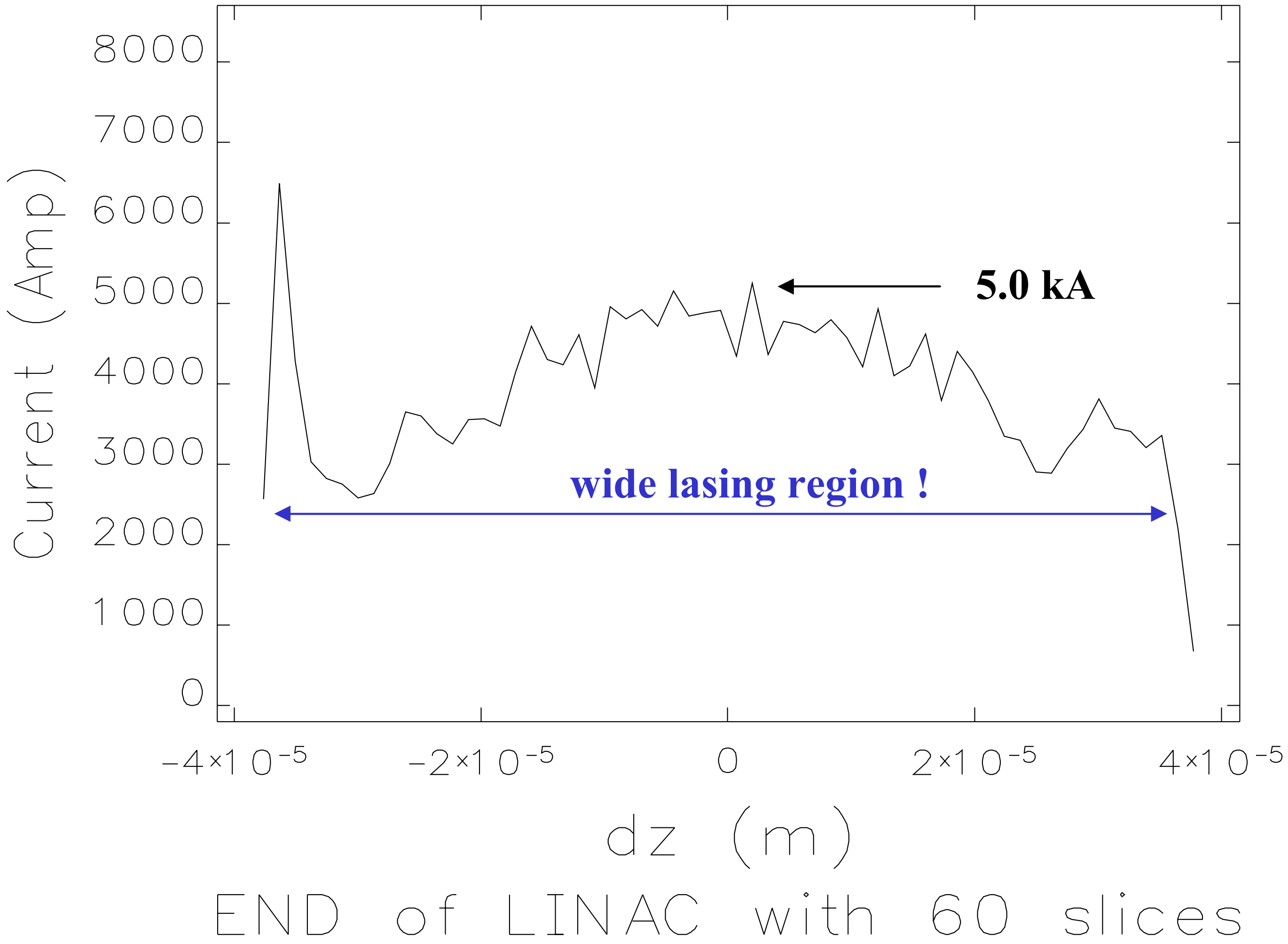


E = 3.389 GeV
σ_δ = 0.033%
σ_x = 68.1 μm, σ_y = 61.9 μm, σ_z = 26 μm
ε_{nx} = 1.116 μm, ε_{ny} = 1.004 μm

Parameter Comparison with TESLA XFEL

Results from the 3rd version Linac Layout for TESLA XFEL Project

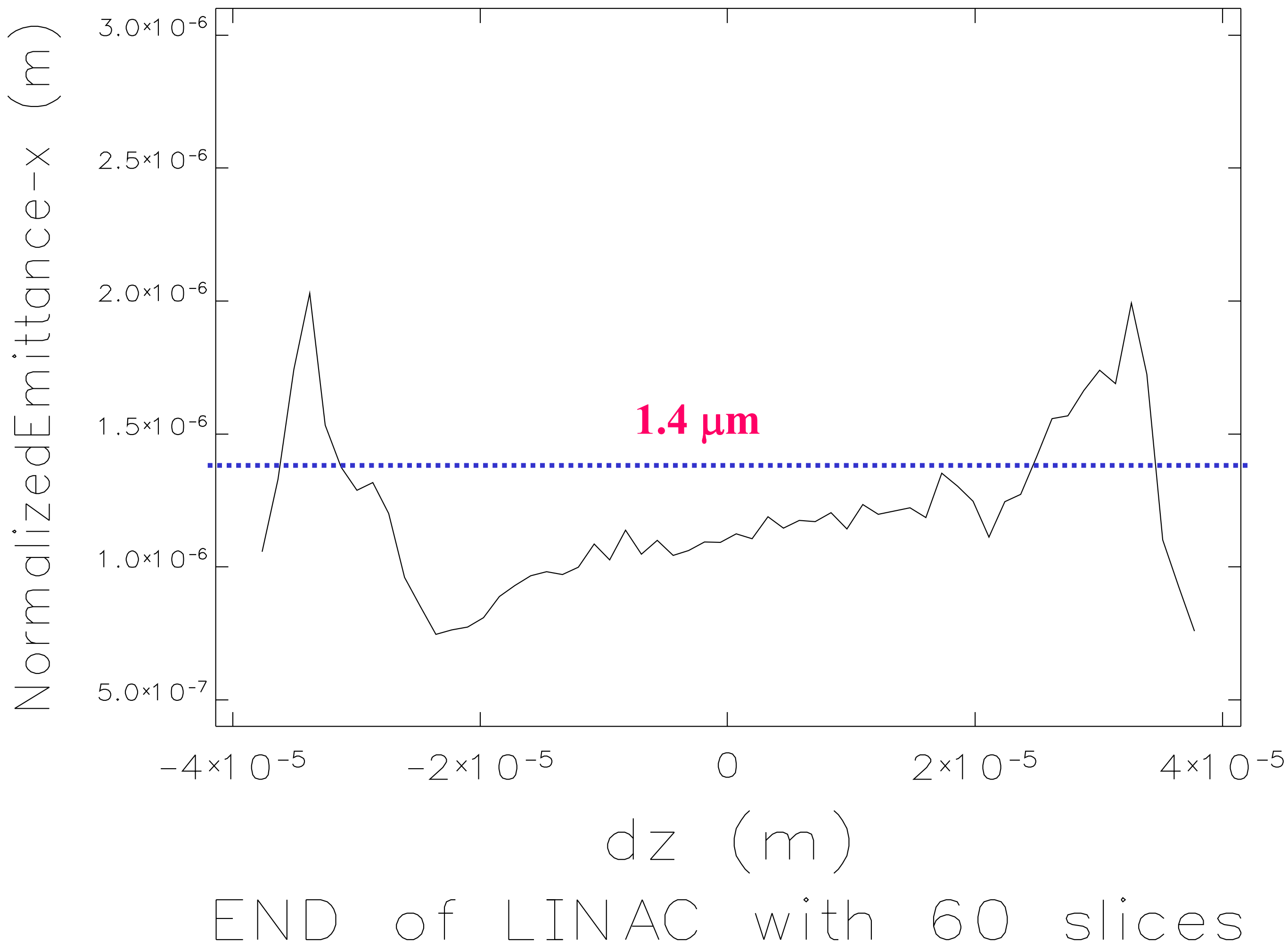
Simulated Particles = 200000



Parameter Comparison with TESLA XFEL

Results from the 3rd version Linac Layout for TESLA XFEL Project

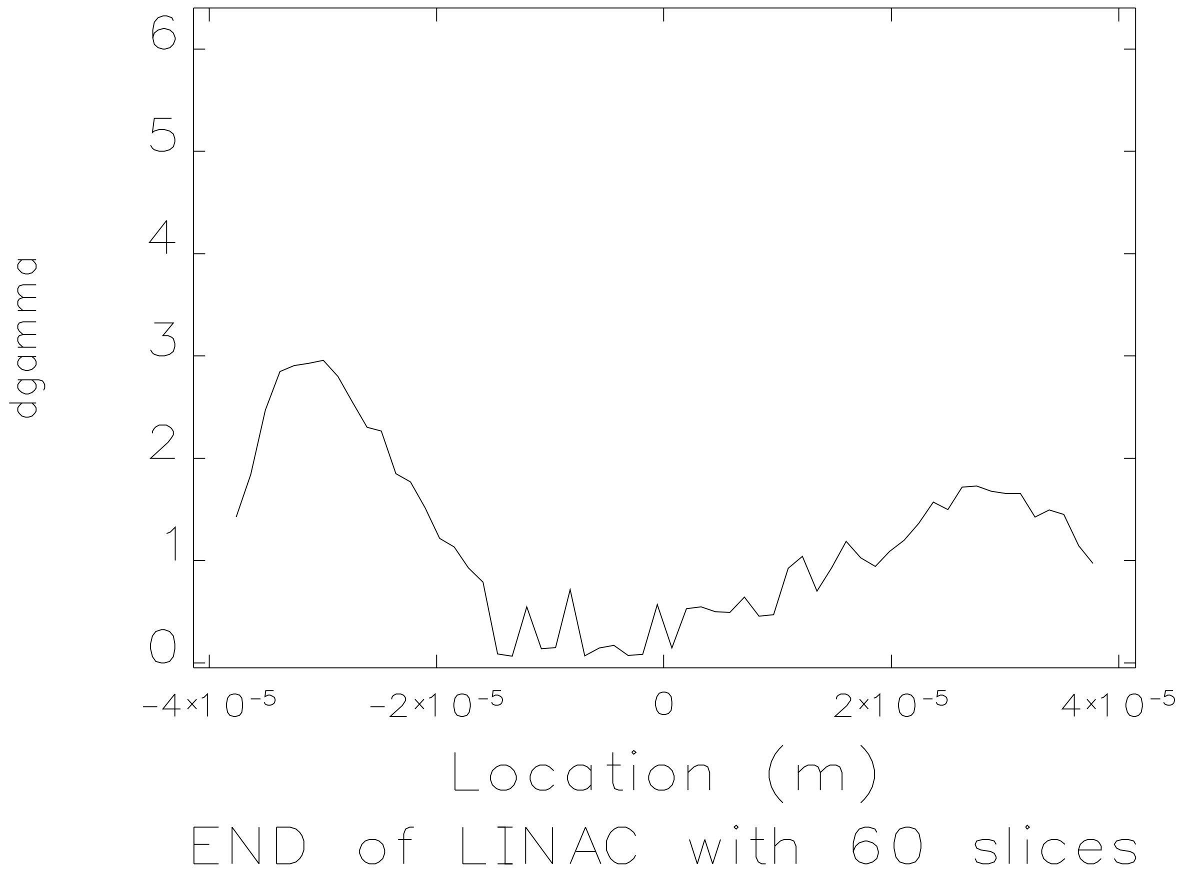
Simulated Particles = 200000



Parameter Comparison with TESLA XFEL

Results from the 3rd version Linac Layout for TESLA XFEL Project

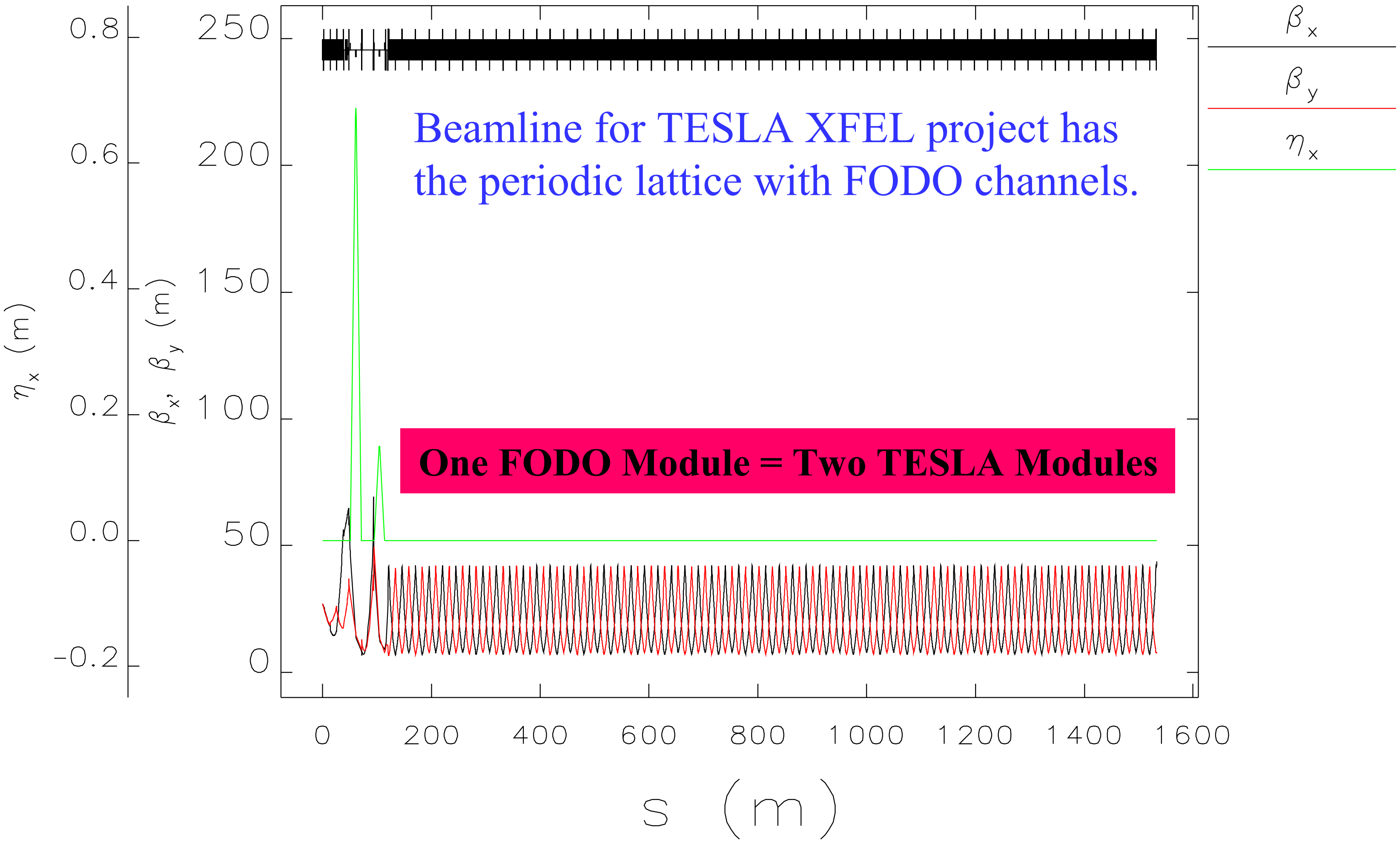
Simulated Particles = 200000



Maximum uncorrelated energy spread : 1.533 MeV @ 20.0 GeV ~ 0.0077% < 0.0125%
Fortunately, the uncorrelated energy spread in the center region is around 0.0013%

Future Plans

Since the PLS existing 2.5 GeV linac dose not have any periodic structure, we can not use FODO channels in the existing PLS linac. But we will optimized the Twiss parameters further to control the chromatic effects there.



Future Plans

S-band Photoinjector will be optimized further.

Twiss paramters around bunch compressors will be optimized further to reduce the chromatic effects.

The beam diagnostic components will be included in the new linac and bunch compressors.

In case of TESLA XFEL, the effect of space charge force is weak enough at 510 MeV although peak current is 5 kA. However we will check its effects at the downstream of PAL XFEL BC2 where energy is about 700 MeV, peak current is about 4 kA for the safety.

In the near future, the jitter and tolerance budgets will be investigated.

Summary & Acknowledgments

We have optimized a lattice for PAL XFEL project by adding a new S-band RF photoinjector, a new 0.5 GeV linac, and two new bunch compressors, to the existing 2.5 GeV PLS linac.

Although peak current is about 4 kA after the second bunch compressor (BC2), the emittance growth at BC2 is about 0.02 μm which is ignorable.

Optimized parameters of PAL XFEL are very promising and good enough to generate 3.0 Å SASE source (or 1.0 Å SASE source with HGHG).

By increasing the beam energy further, we may get a better margin in the uncorrelated energy spread.

Twiss parameters should be optimized further to reduce the emittance growth due to chromatic effects, and jitter tolerance should be investigated.

Yujong Kim sincerely thanks K. Flöttmann, S. Schreiber, J. Rossbach, R. Brinkmann, D. Trines, Z. Huang, and K.-J. Kim for their encouragements of this work and many useful comments and discussions.